Complexity Aspects in Design for Sustainability

M.J.T. Schroijen

This planet has — or rather had — a problem, which was this: most of the people living on it were unhappy for pretty much all of the time. Many solutions were suggested for this problem, but most of these were largely concerned with the movement of small green pieces of paper, which was odd because on the whole it wasn't the small green pieces of paper that were unhappy.

The Hitchhiker's Guide to the Galaxy
D. Adams

Complexity Aspects in Design for Sustainability

Proefschrift

ter verkrijging van de graad van doctor
aan de Technische Universtiteit Delft,
op gezag van de Rector Magnificus prof.ir. K.C.A.M. Luyben,
voorzitter van het College voor Promoties
in het openbaar te verdedigen op vrijdag 10 juni 2011 om 10:00 uur
door

Marcel Josephus Theodorus SCHROIJEN

ingenieur luchtvaart en ruimtevaart
geboren te Heythuysen, Nederland.

Dit proefschrift is goedgekeurd door de promotor:
Prof.dr.ir. M.J.L. van Tooren

Samenstelling promotiecommissie:

Rector Magnificus,	voorzitter
Prof.dr.ir. M.J.L. van Tooren,	Technische Universiteit Delft, promotor
Prof.dr. R. Curran,	Technische Universiteit Delft
Prof.ir. J.J. Hopman,	Technische Universiteit Delft
Prof.dr. C. Witteveen,	Technische Universiteit Delft
dr. D. DeLaurentis,	Purdue University
dr.Eng. J. Sobieski,	NASA Langley Research Center
ir. R.N.H.W. van Gent,	Technische Universiteit Delft

keywords: sustainable design, complexity, agent-based modelling and simulation, multidisciplinary design optimization, Bayesian statistics

ISBN/EAN: 978-90-9026197-3

Cover picture: Meissendorfer Teiche, courtesy of M.J. Schroijen.

Printed in the Netherlands.

The research reported in this thesis is performed within the CleanEra project at the Delft University of Technology.

Summary

Complexity Aspects in Design for Sustainability

Despite large efforts to find technical solutions to counter the growing environmental impact of our current transport systems, these systems show an increasing impact on the demand for natural resources and on the environmental condition for humanity. Since our transportation systems are complex, dynamic and interconnected, the effect of changes in vehicles, infrastructure and logistics are hard to predict, let alone control. This difficulty of predicting the impact is caused by the dependence on stakeholder behaviour. As a consequence, this problem of impact reduction is classified as a *"no technical solution problem"*. For this type of problem technology can only *aid* in finding and providing solutions. Taking aviation as a challenging example, it is identified that this complex system-of-systems is compromised of many (different) interacting decision making stakeholders, all affecting the environmental impact of an aircraft technology development programme. In this thesis the limited definition of a stakeholder is given by;

> *A stakeholder for the aircraft technology development programme is (by definition) any group or individual who can affect the achievement of the programme's objectives*,

which is based on the premiss that any group or individual affected by the externalities of the programme is empowered by legislation to affect the programme's achievements. Evaluation and design of sustainable aircraft should incorporate the needs of *all* stakeholders. A framework capable of this incorporation can be used by governments, stakeholders and corporations to predict the overall impact of the technology and not be limited to the system level consideration. This allows more appropriate legislation and upfront intervention in and steering of technology development programmes.

A framework for anthropogenic environmental impact evaluation needs to implement methods addressing the coupled effect of human behaviour and technological impact. This requires such a framework to address (human induced) complexity in Complex, Large-Scale Integrated Open Socio-technical Systems (CLIOS) to determine the effect of technologies and methodologies on the environmental impact of aviation.

Four types of complexity have been identified and are to be addressed by the framework: 1) evaluative, 2) behavioural, 3) structural and 4) modelling complexity. At the system-of-systems level: *Evaluative* complexity stems from the multiple interacting stakeholders in aviation and their conflicting needs from the single aircraft design. *Behavioural* complexity in aviation arises from the fact that the exact impact of a new aircraft system, i.e.

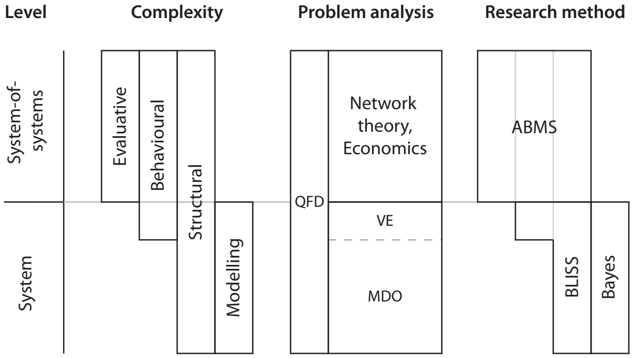


Figure S.1: Schematic overview of system level, complexity and available and proposed tools addressed in this thesis.

an external disturbance, on the system-of-systems impact is hard to model or predict with accuracy. Finally, the large number of intertwined stakeholders to be considered in the evaluation of the environmental impact results in *structural* complexity. At the system level the coupled nature of the novel systems introduces *behavioural* complexity. The method of decomposition used in the design to address this complexity introduces *structural* complexity. Finally, *modelling* complexity arises from the fact that the validity of the results, produced by first principle and high fidelity tools, remains uncertain for novel and unconventional configurations. No single tool can address all complexities at once. However, to support the steering of technology towards sustainability a framework is devised to evaluate the environmental impact of a novel technology at the system-of-systems level. Two goals have been formulated and addressed. At the system-of-systems level:

> *Devise a method that couples system level impact and human/ organizational/ societal behaviour in order to evaluate the true impact of a technology at the system-of-systems level*,

and at the system level:

> *Investigate the early stages of design to identify the shortcomings of the current design method in reducing the environmental impact and illustrate this using the variety of proposed technical solutions.*

As the overarching framework, connecting the two goals Quality Function Deployment (QFD) is used in combination with Network Theory, Economics, Value Engineering (VE) and Multidisciplinary Design Optimization (MDO). To extend the capabilities of these methods three challenges to be addressed by appropriate tools are formulated:

1) *Address the complexities at the system-of-systems level. In particular the modelling of stakeholders in a computational domain and the coupling of behaviour, technology and the resulting environmental impact.*
2) *Address the structural and behavioural complexity present in the conceptual design of a system, using a multidisciplinary design optimization framework.*

3) *Address the modelling complexity and in particular the uncertainty in model errors occurring for (novel) technologies.*

The addressed complexities and their corresponding methods of addressing them are shown in Figure S.1.

Challenge 1 The tool used to solve the first challenge for the integrated stakeholder approach was the Agent Based Modelling and Simulation (ABMS) framework, using economic, game and network theory to address the evaluative, behavioural and structural complexity present at the system-of-systems level. This tool treats stakeholders as agents, i.e. elements, in a simulation environment. Each element is characterized by its internal behavioural response. This allows for the easy exchange of agents and/or behaviour resulting in a flexible tool, capable of addressing the changing system-of-systems. The usability of this tool in predicting environmental impact at the system-of-systems level was shown using a show case of MagLev take-off system. Changes occur in the real system, but also in the insights on agent behaviour. For the quantitative behaviour modelling the identification of stakeholder goals and strategies was found more robust than inference from previous behaviour. The difficulty of identifying these goals and strategies was illustrated using the Prandtl Plane show case.

Challenge 2 To address the second challenge, the BLISS tool was used. The implementation of the BLISS framework is used to evaluate the show case of the Blended Wing Body (BWB). The BLISS framework does provide the designer with a tool to analyse the system, composed of (closely) coupled disciplines. Even though the found solution was not feasible due to the limited model design space implemented, the BLISS framework obtained a solution for the BWB which was improved from the initial condition, successfully addressing the second challenge.

Challenge 3 The third challenge is addressed using a probabilistic framework. For this challenge the design problem has been limited to a single discipline, eliminating structural complexity from this treatment. The procedure of validation is illustrated using the validation of a potential flow model to support the (conventional) design of multi engine propeller aircraft. Uncertainty is introduced into the model design space when validation data is not available. Error prediction and the uncertainties involved are facilitated using the Bayes probabilistic framework. This tool is illustrated using the novel Coandă vehicle. The probabilistic framework was unable to eliminate the uncertainty in error prediction but able to quantify it. This provides the designer with a tool to quantify the uncertainty in his prediction based on his own assumptions.

This thesis tried to identify and provide solutions to the sustainable conundrum. One challenge to be overcome is how and which stakeholders should be given influence on the design. In this thesis it has been assumed that the earth carrying capacity is known and quantified and represented by all stakeholders. These assumptions are subject to political and scientific debate and their validity has not been considered in this thesis. However, they determine what is considered “desirable” in this thesis and need further substantiation. Despite the large influence of these issues on the environmental impact, advances in technology can *aid* in the reduction of environmental impact at the system-of-systems

level. For more sustainable products this requires an integrated approach, both at the system-of-systems level and at the system level. Consequently, projects aiming at the reduction of environmental impact should at least address these stakeholder interactions and project focus should be broadened from mere technology improvement towards true environmental impact reduction incorporating the needs of the *true* stakeholders.

Technology improvement requires a prediction of stakeholder behaviour, which is one of the most challenging elements. This research has only focussed on how technology changes the behaviour of stakeholders. Limited effort has been put in the question of how the behaviour can be changed (by technology or otherwise) to limit anthropogenic impact. That is: can behaviour be changed using technology to stimulate decisions in the group interest instead of individual interest and as such efficiently steer technology towards the needs of a sustainable society. The current predictive capability has to be extended to not only predict the environmental impact, but also “design the environment” in which the technology operates. As a basis for this Method Design could be used in extension to the currently used game-theoretic predictions of stakeholder behaviour. The ABMS approach can still be used to support the prediction of environmental impact effects caused by deliberate changes in the environment.

As a first improvement for a sustainable human society, it was proposed that all product developments should include upfront evaluations of the desirability of the development of the product. This evaluation of the desirability has to account for the stakeholder behaviour and stakeholder interactions and should replace the “find a market for the product” criterion. However, this preemptive check on product desirability hampers innovation as most technologies cannot be shown to comply due to a lack of information. This lack of information should not prevent innovation but requires constant re-evaluation of its desirability. As a consequence, the reversibility of a technology, that is the amount of effort required to revert its impact, needs to be considered as well. Appropriate means to incorporate the reversibility costs in the technology desirability evaluation need further study in line with risk analysis.

Although the search for a generic and all-at-once tool is futile due to the complexity present in real world problems, the study of the elements and their interactions is still necessary. The tools proposed in this thesis provide a complete framework, however they are still loosely coupled. QFD provides the glue between their results, but this bond needs to be reinforced. A more thorough study is required on how the three proposed tools interact and how their predictions can be applied to improve product design. In particular the complementary views provided by the tools can contribute to the “design for sustainability” and arrive at a sustainable future for aviation. Future research should be focussed on the interaction of the various tools and how they can be improved to better support design for sustainability using A real design process, including all stakeholders, their interactions as well as the complexities of designing a product. This will be the true test of the set of tools and their ability to improve product sustainability.

Samenvatting

Complexiteitsaspecten in Ontwerp voor Duurzaamheid

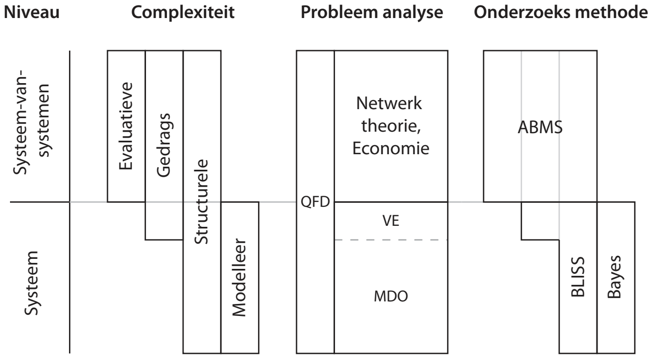
Ondanks grote inspanningen om een technische oplossing te vinden voor de groeiende omgevingsbelasting van het huidige transportsysteem, is er nog steeds een toename waar te nemen in de vraag naar grondstoffen en in invloed op de leefbaarheid van de omgeving voor de mensheid. Omdat het huidige transportsysteem complex, dynamisch en gekoppeld is, zijn de effecten van veranderingen in voertuigen, infrastructuur en logistiek moeilijk te voorspellen, laat staan te beheersen. De moeilijkheid om omgevingsbelasting te voorspellen wordt veroorzaakt door de afhankelijkheid van het gedrag van de belanghebbenden. Als gevolg hiervan is dit probleem geclassificeerd als een *"probleem zonder technische oplossing"*. Voor dit type probleem is technologie slechts een deel van de oplossing.

Als uitdagend voorbeeld is de luchtvaart genomen, waarbij luchtvaart geïdentificeerd is als een complex systeem-van-systemen (SvS). Een dergelijk SvS wordt gekenmerkt door vele diverse elkaar beïnvloedende maar individueel beslissende belanghebbenden. Elk van deze belanghebbenden beïnvloed de omgevingsbelasting van een vliegtuigtechnologie in ontwikkeling. In deze dissertatie is een beperkte definitie van een belanghebbende gebruikt;

> *Een belanghebbende in een vliegtuigtechnologie ontwikkelingsprogramma is (per definitie) elk(e) groep of individu die/dat het behalen van de doelstellingen van het programma kan beïnvloeden.*

Deze definitie is gebaseerd op de aanname dat elk(e) groep of individu, beïnvloed door de externaliteiten, het vermogen krijgt om via wetgeving de doelstellingen van het programma te beïnvloeden. Het evalueren en ontwerpen van een duurzaam vliegtuig moet derhalve de wensen van *alle* belanghebbenden beschouwen. Een raamwerk, dat de wensen van alle belanghebbenden beschouwt, moet worden gebruikt door regelgevers, belanghebbenden en organisaties om de algehele invloed van de technologie te voorspellen en is niet gelimiteerd tot systeem beschouwingen. Dit staat meer realistische wetgeving, preventieve interventie en preventieve bijsturing van technologie ontwikkelprogramma's toe.

Een dergelijk raamwerk dat de antropogene omgevingsinvloed evalueert, heeft methoden nodig die de invloed van menselijk gedrag op de technologie externaliteiten meeneemt. De (menselijke) complexiteiten van Complexe, Grootschalige Geïntegreerde Open Sociaaltechnische systemen moeten door het raamwerk worden aangepakt om het effect van technologieën en methodologieën op de omgevingsbelasting van de luchtvaart te bepalen. Vier complexiteitstypen zijn geïdentificeerd en moeten worden aangepakt door het



Figuur S.1: Schematisch overzicht van systeem niveau, complexiteit en beschikbare en voorgestelde gereedschappen, zoals behandeld in deze dissertatie.

raamwerk: 1) evaluatieve, 2) gedrags-, 3) structurele en 4) modelleercomplexiteit. Op het SvS niveau: *Evaluatieve* complexiteit ontstaat door de veelvoud aan belanghebbenden in de luchtvaart. Hun conflicterende behoeften moeten gecombineerd en vertaald worden tot één vliegtuigontwerp. *Gedrags*complexiteit in de luchtvaart ontstaat doordat het precieze effect van een nieuw vliegtuig systeem moeilijk te modelleren en voorspellen is, met name de externe veranderingen op het SvS niveau. Ten slotte resulteert de grote hoeveelheid aan te beschouwen belanghebbenden in *structurele* complexiteit. Op systeem niveau introduceren de multifunctionele componenten en hun interacties in de aangedragen nieuwe oplossingen *gedrags*complexiteit. De methode die wordt gebruikt om deze complexiteit aan te pakken in het ontwerp, namelijk decompositie, resulteert in *structurele* complexiteit. Ten slotte ontstaat *modelleer*complexiteit omdat de betrouwbaarheid van wiskundige modellen niet met zekerheid bepaald kan worden. Dit is met name het geval bij onconventionele configuraties en technologieën.

Geen enkel gereedschap kan al deze complexiteiten in een keer aanpakken. Desalniettemin is er een raamwerk gecreëerd om de omgevingseffecten van een nieuwe technologie te bepalen en zo het product ontwerp voor duurzaamheid te ondersteunen. Twee doelen zijn geformuleerd en aangepakt. Op het SvS niveau:

> *Ontwikkel een methode die de systeeminvloed koppelt aan menselijk/ organisatorisch/ samenlevingsgedrag om zodoende de daadwerkelijke invloed van een technologie op SvS niveau te kunnen evalueren*,

en op systeem niveau:

> *Onderzoek de vroege ontwerpstadia om de tekortkomingen te identificeren van de huidige ontwerpmethoden om de omgevingsinvloed te reduceren en illustreer dit gebruik makend van de variëteit in voorgestelde technische oplossingen.*

Voor het allesomvattende raamwerk zijn de twee doelen gekoppeld door middel van “Quality Function Deployment” (QFD) aangevuld met netwerk theorie, economie, Value Engineering (VE) en Multidisciplinaire Design Optimalisatie (MDO). Om de mogelijkheden van deze methoden uit te breiden zijn drie uitdagingen geformuleerd welke aangepakt dienen te worden door geschikte gereedschappen:

1) *Pak de complexiteiten op het systeem-van-systemen niveau aan. In het bijzonder het modelleren van belanghebbenden in een software omgeving en het koppelen van gedrag, technologie en de resulterende omgevingsinvloed.*
2) *Pak de structurele en gedragscomplexiteiten aan die aanwezig zijn in het voorontwerp van een systeem, waarbij gebruik wordt gemaakt van een multidisciplinair design en optimalisatie raamwerk.*
3) *Pak de modelleer complexiteit aan en dan met name de onzekerheid in model fouten ontstaan bij (nieuwe) technologieën.*

De bovenstaande complexiteiten en corresponderende methoden en gereedschappen zijn getoond in Figuur S.1.

Uitdaging 1 Het gereedschap dat is gebruikt om de eerste uitdaging op te lossen is een Agent Based Modelling and Simulation (ABMS) raamwerk. Hierbij is gebruik gemaakt van economische, spel- en netwerktheoretische elementen om de evaluatieve, gedrags- en structurele complexiteiten aan te pakken. Dit gereedschap behandelt belanghebbenden als “agents”, dat wil zeggen elementen, in een simulatie omgeving. Elk element wordt gekenmerkt door zijn interne gedragsmodel. Dit staat eenvoudige uitwisseling van agents en/of gedragsmodellen toe, wat resulteert in een flexibel gereedschap, dat in staat is om de veranderingen in het SvS te vatten. De bruikbaarheid van ABMS ter voorspelling van de omgevingsinvloed op SvS niveau is geïllustreerd met de MagLev technologie. De veranderingen die nodig zijn aan de ABMS implementatie kunnen voortkomen uit de daadwerkelijke systeem-samenstelling, maar ook uit inzichten in het gedrag van belanghebbenden. Om het gedrag kwantitatief te modelleren is het identificeren van doelen en strategieën het meest robuust gebleken. De moeilijkheden die optreden bij het identificeren van de doelen en strategieën zijn geïllustreerd met behulp van de Prandtl Plane (Box wing).

Uitdaging 2 Om de tweede uitdaging aan te gaan is Bi-Level Integrated System Synthesis (BLISS) gebruikt. De implementatie van BLISS is gebruikt om een Blended Wing Body ontwerp te evalueren en optimaliseren. Het is aangetoond dat BLISS de ontwerper een gereedschap in handen geeft om een systeem te analyseren en optimaliseren dat bestaat uit (nauw) gekoppelde disciplines. Ondanks dat de gevonden oplossing niet uitvoerbaar bleek doordat de gebruikte ontwerpruimte te klein was, bleek BLISS in staat om een verbetering in het ontwerp te bewerkstelligen. Dientengevolge is de tweede uitdaging succesvol door BLISS aangepakt.

Uitdaging 3 De derde uitdaging is aangepakt door middel van een probabilistisch raamwerk. Voor deze uitdaging is het ontwerpprobleem beperkt tot een enkele discipline. Zodoende is de interdisciplinaire structurele complexiteit geëlimineerd. De procedure van validatie is geïllustreerd aan de hand van een aerodynamisch potentiaal stromingsmodel om het ontwerp van een meermotorig propellervliegtuig te ondersteunen. Daar waar meetgegevens ontbreken in de ontwerpruimte is onzekerheid geïntroduceerd. De voorspelling van de fout en de daaraan gelieerde onzekerheden worden onderzocht door middel van een Bayes probabilistisch raamwerk. Het gebruik van dit gereedschap is geïllustreerd door gebruik te maken van het nieuwe Coandă micro voertuig concept. Het gereedschap bleek niet in staat om de onzekerheden in foutvoorspelling weg te nemen, maar wel om ze kwantificeerbaar te maken. Dit geeft de ontwerper de mogelijkheid om de onzekerheden in de foutvoorspelling te schatten gebaseerd op de aannames gedaan in de gebruikte modellen.

Deze thesis probeert oplossingsmogelijkheden te identificeren en oplossingen aan te dragen om het duurzaamheidsvraagstuk op te lossen. Een van de belangrijkste uitdagingen die dient te worden opgelost is; op welke manier belanghebbenden invloed zouden moeten krijgen op het ontwerpproces. In deze thesis wordt aangenomen dat de capaciteit van de aarde (limiet) beperkt, meetbaar en bekend is. Verder is aangenomen dat belanghebbenden de complete set van limieten vertegenwoordigen. Deze aannames zijn echter nog onderhevig aan politieke en wetenschappelijke discussie. De uitkomst hiervan heeft grote gevolgen voor de mate van “wenselijkheid” van de oplossingen die zijn aangenomen en dienen daarom verder onderzocht te worden.

Ondanks de grote invloed van deze probleemstelling op de omgevingsinvloed kunnen verbeteringen in technologie *helpen* bij het reduceren ervan. Voor duurzamere producten is een geïntegreerde aanpak nodig op systeem- en op SvS niveau. Als gevolg hiervan, moeten projecten met de intentie om de omgevingsinvloed te reduceren tenminste deze belanghebbenden en hun interacties meenemen. De project focus moet daarom uitgebreid worden van de huidige technologie verbetering naar ware duurzaamheidsverbetering. Deze verbetering vereist een voorspelling van het gedrag van de belanghebbenden, wat een van de meest uitdagende elementen is. Dit onderzoek heeft zich voornamelijk gericht op hoe technologie het gedrag verandert en heeft niet de intentie gehad om de vraag op te lossen hoe gedrag zou moeten worden veranderd om het groepsbelang voorop te stellen. Hiervoor is een “omgevingsontwerpgereedschap” nodig waarvoor ABMS en “Method Design” de basis kunnen vormen.

Als een eerste verbetering voor een duurzame menselijke beschaving zou van alle producten en ontwikkelingen vooraf moeten worden bekeken of ze een “wenselijke” verandering teweegbrengen. Deze preventieve controle vertraagt of houdt innovatie zelfs tegen, omdat niet altijd direct kan worden bepaald wat wenselijk is. Om dit op te lossen zou de omkeerbaarheid van de effecten meegenomen moeten worden. Hiervoor zou de moeite die het kost om de gevolgen ongedaan te maken een goede maat zijn. Als een eerste stap zou een risicoanalyse kunnen worden ingezet om deze overweging mee te nemen.

Hoewel de zoektocht naar een generiek all-at-once gereedschap tevergeefs is gebleken door de aanwezige complexiteiten, heeft het onderzoeken van de elementen en hun interacties zeer waardevolle informatie opgeleverd. De gereedschappen voorgesteld in deze thesis creëren een compleet raamwerk, maar hun koppeling is nog steeds zwak. Om deze koppeling te verbeteren is onderzoek nodig naar hun interactie en hoe hun complementaire kijk op de wereld kan bijdragen aan een duurzamere toekomst voor de luchtvaart. Toekomstig onderzoek zal zich moeten richten op de interactie tussen de gereedschappen toegepast op een productontwerp. Het aanpakken van de extra optredende complexiteiten levert inzicht in de bijdrage van de gereedschappen aan een duurzamere productontwikkeling. Dit moet leiden tot de ontwikkeling van daadwerkelijk duurzame producten.

Contents

Appendices

Chapter 1. Sustainable design

"The chief cause of problems is solutions."
Eric Severaid.

Our current systems for transport of people and goods show an increasing impact on the demand for natural resources and on the environmental condition for humanity. Since our transportation systems are complex, dynamic and interconnected, the effect of changes in vehicles, infrastructure and logistics are hard to predict, let alone control[179]. One transportation system in particular, air transport, poses a challenge since conventional technologies and improvements are found insufficient to achieve the required decrease in adverse environmental impact[138]. For the design of a novel, more sustainable air transport system, a new design approach is required both for the complete system and its elements. This approach should incorporate the — conventional/ extended — technology environmental impact assessment while accounting for the behaviour of stakeholders. Accounting for the behaviour of all stakeholders poses a significant challenge as a single aircraft manufacturer has $100+$ potential airline customers, who together transport $100+$ million passengers a year. Not to mention the 6 billion people living on this planet, who are affected directly or indirectly by aviation. Furthermore, an important component of the behaviour to be incorporated is the complex interaction of product demand and supply and the resulting effect on the environmental impact of the transport systems. Since modelling the complete system, comprised of many continuously adapting elements, is unthinkable, the challenge lies in identifying relevant elements and appropriately modelling them, while mindfully reflecting the boundary effects of the unmodelled elements[179]. This thesis provides a framework of methods and tools supporting the design of sustainable elements for transport systems.

1.1 Environmental boundaries and human behaviour

Human society has to face the challenge that its actions have an adverse effect on a global scale. The climate changes in ways never encountered in history before, due to excess consumption of fossil fuels and radical changes to the landscape — by large amounts of wood-cut, fishing and bio-industry. Global effects can originate from; 1) impact of single activities sufficiently large to directly alter the earth's system, like the three gorges dam, or 2) activities sufficiently large in number and spread over the earth, with a global effect, e.g. transport. The former activity-category already received a lot of attention in terms of impact considerations due to its clear effect on the environment, whereas the latter is more difficult to identify and assess due to dispersion and seemingly inconsequent small scale effects. Nevertheless, the large number of activities surmounts to a significant environmental impact. This impact includes, but is not limited to, (non-)renewable resource use or waste accumulation, resulting in the destabilization of ecological systems. Ehrlich and Holdren[31, 54] captured this anthropogenic impact in

$$I = P(T)F(P,T) \tag{1.1}$$

where I represents the anthropogenic impact on the environment in appropriate units, e.g. anthropogenic energy consumption, resource depletion or waste accumulation, P the size of the human population, e.g. number of humans, and F is a function which measures per capita impact. F is a function of P depending on the impact measure chosen[31, 54] and the technology T employed by the population to support their behaviour. Despite the simplifications, Equation 1.1, shows the significant impact generated by a large population notwithstanding a small per capita impact. The current contribution of this accumulated anthropogenic impact on the environment has become sufficiently large to affect the earth at a global scale. Therefore, to be able to keep our wealth and health and allow future generations to enjoy similar prospects a change — in lifestyle — is required to limit the adverse component of these anthropogenic effects[27] to create a *sustainable society*. The left and right hand side of Equation 1.1 need further elaboration;

1) what are appropriate measures for environmental impact and is there a maximum allowable impact for a continued habitable planet. This is addressed by investigating the physical phenomena affecting and (de)stabilizing the earth system resulting in *physical boundaries*.
2) what causes the anthropogenic impact growth and will it be self-regulating. This elaboration is focussed on the development of *human behaviour* in response to the environmental boundaries.

Both will be addressed in the following sections, followed by some concluding remarks on the reduction of anthropogenic impact focussing on technology.

1.1.1 Physical boundaries

Sustainable, in the context of a sustainable society, means "*to perform (an action) for indefinite periods of time*"[12], which is not represented in the left part of Equation 1.1. I only provides a measure for the impact of human activities at an instant in time or over the period of consideration. There is ample support that the anthropogenic impact I cannot grow unbounded in our finite universe[12, 27, 56, 57]. Even the sun's incredible energy, seemingly infinite from our current energy consumption standards, is limited. The concept of *carrying capacity* is therefore defined as quantifiable boundaries which should not be crossed if the goal is to support humanity for indefinite periods of time, and the earth is not to be changed by anthropogenic activities[1].

---

[1] Continuation of humanity is not guaranteed as it leaves the possibility of non-anthropogenic change of nature open. The considerations are therefore limited to anthropogenic impact as a means of not decreasing the time of

Before continuing with the identification of appropriate measures to describe impact, a mathematical formulation to describe impact limits in time is formulated. Consider a function $I(t)$ describing anthropogenic impact at each instance in time t, define $g(t)$ as a function of the earth's carrying capacity with time, and $C(t)$ the reduction of impact in time by the "cleaning" ability of the earth system. For the earth system to stabilize to a sustainable state the anthropogenic impact should be limited to the earth's carrying capacity,

$$\lim_{t\to\infty} \frac{\int_{-\infty}^{t} \big(I(\tau) - C(\tau)\big)\mathrm{d}\tau}{g(t)} \leq 1 \tag{1.2}$$

which states that the impact of all human impacts up to time t, accounted for the natural cleaning ability, should be lower than the earth's carrying capacity at any given instant in time t. To clarify the equation, consider as an example the impact of carbon dioxide. Then I represents the production of carbon dioxide per unit of time by humanity. C is the natural cleaning capacity per unit of time, which is dependent on the earth system state and consequently on the anthropogenic activities, e.g. deforestation and capturing of carbon dioxide in underground storage facilities. The difference per unit of time is to be integrated over time to arrive at the overall impact of humanity at time t. This total impact has to be lower than the maximum impact $g(t)$ required to support the human population at this time t. As a consequence this maximum impact is dependent on the population to be supported. Due to the maximum impact allowed, boundaries exist in order to support humanity for indefinite periods of time, this boundary is dubbed the earth's carrying capacity. Hence for a sustainable society a necessary but insufficient condition would be asymptotic growth limited by the earth's carrying capacity. The insufficiency stems from the fact that the function $\int_{-\infty}^{t} \big(I(\tau) - C(\tau)\big)\mathrm{d}\tau$ should not cross the unknown stability boundary $g(t)$. This appears to be an issue not easily identifiable by humans, since human time horizons are much lower than infinity, in the order of days and years, not the required millions of years[97]. One safe interpretation would be to limit the anthropogenic impact $I(t)$ at any time to the — unfortunately unknown — cleaning ability of the earth $C(t)$.

Further support for the existence of stability limits — boundaries — to the earth's ecosystem is provided by Rockstrom et al.[57]. They argue that the earth system has been remarkably stable during the Holocene but is currently stressed by anthropogenic activity. Their concept of the earth system as a stable system, whose stability is affected by humanity, provides a qualitative view on the possibility of abrupt and severe changes from 1) stressing the earth system beyond its stability boundary, or 2) destabilizing the system itself. In local ecosystems these abrupt and severe changes between stable points have been observed[97]. At a global scale the alternation between ice ages and relative warm periods can also be interpreted as switching between two stable points. To prevent the earth system from shifting from its current stable state, a set of safe operating boundaries is proposed based on current knowledge and understanding of the earth system[57]: 1) climate change, 2) ocean acidification, 3) stratospheric ozone depletion, 4) nitrogen and phosphorus cycle, 5) global fresh water use, 6) change in land use, 7) bio-diversity loss, 8) atmospheric aerosol loading and 9) chemical pollution. Each of these categories represents (a combination of) multiple quantities, whose current estimates are shown schematically in Figure 1.1. This set of boundaries is incomplete as human understanding of the operation of the earth system is limited. Moreover, the exact values for a safe operating

---

existence of a human inhabitable environment.

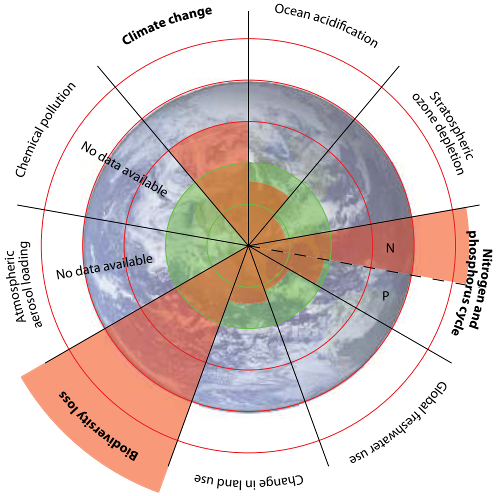


Figure 1.1: Boundaries as identified by Rockstrom et al., adapted from Rockstrom et al.[57]. [earth background image, courtesy of NASA.]

space are still open for debate[34], as well as which boundary, or combination of boundaries, is critical. For this thesis it is assumed that human impact is beyond the earth's capacity on two of them and close on, at least, two others. Quantifying these boundaries is difficult, but reasonable estimates carry the power to convince people of their existence and importance. Furthermore, they provide the means of identifying and managing the impact of human behaviour. The identification of the boundaries allows environmental impact to be defined as the influence of a system or action on these boundaries, in the broadest sense of both influence and action. Despite the uncertainty and unknowns in the quantification of these limits, the future society has to cope with boundaries.

1.1.2 Behavioural issues

No matter the interpretation of the left side of Equation 1.1, the allowable anthropogenic impact is limited. The right side of Equation 1.1 is interpreted as human behaviour and its inevitable impact on the environment. Technology is seen in this context as an enabler of human behaviour. This right side is composed of two parts, population size and the impact of this population due to its actions. If one of these parts increases, an equivalent decrease in the other part is required. Since it is inherent to humans to want to improve wealth, i.e. improve the quality of life, and the size of the human population is growing, the natural factor investigated to reduce human impact is the impact of technology providing the life style.

In order to provide a final solution, technology is required to cope with *any* continuous growth in population or affluence to maintain a finite environmental impact. To avoid environmental impact altogether, one should aim for zero environmental cost technologies. Unfortunately, reduction of technological impact T is bounded[34]. The fundamental reason for the limit to this impact reduction originates from the fact that the earth is a closed

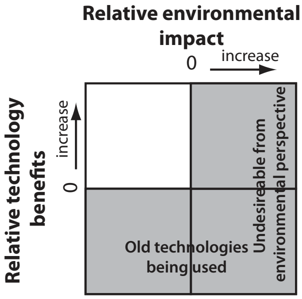


Figure 1.2: Area of interest for the product design to be able to reduce environmental impact in a free market.

thermodynamic system where Newtonian physics are applicable[183, pp.11]. Technologies and products require resources and energy for their production and operation. Consequently, in each technology's life cycle externalities can be found which affect the overall environmental cost of transport systems like aviation. As a consequence, unwanted side-effects are inherent to all technologies, e.g. resource use. Solution or elimination of one side-effect results in a — known and unknown — shift of adverse environmental impact. Furthermore, the view of technology as the final solution assumes that technology can be improved in isolation, without affecting behaviour F or population size P. The inadequacy of this implicit assumption of *ceteris paribus* — everything else being equal — is caused by the coupling of technology impact, behaviour and population size. As a consequence, the approach should be to balance the product's environmental costs with the benefits. How this balance should be achieved is still an issue of political debate.

As an example of such a coupling, consider the inherent coupling of behaviour and technology in the success of a technology. This success of introduction of any technology is determined by the willingness of customers to adopt it. The success is measured here as the number of products incorporating the technology that are being sold or used. The willingness to adopt a technology is determined by the perceived benefit experienced by the customers as well as the manufacturers. That means that both have to *voluntarily* purchase and manufacture the product. From this it must be concluded that for any technology to have an impact in a free market, additional (perceived) benefits for both the manufacturer and customer have to be generated by the product. On the other hand, a reduction in environmental impact can only be achieved by reducing product environmental impact. Both considerations are shown schematically in Figure 1.2, where the only viable option for a new technology is the upper left region, increasing value and reducing environmental impact. The coupling between technology impact and behaviour becomes apparent when this added value encourages increased use, alternative use or both. The environmental impact, per product or per use, might be reduced, but the additional or alternative use, affects and possibly increases overall impact. This is a strong indication that, in order to determine the overall environmental impact, the resulting use, i.e. behaviour, should be incorporated in the technology impact evaluation as well. The issue is aggregated for novel technologies due to the often unexpected and significant adaptation of behaviour[41, 128, 179].

Nevertheless, for constant behaviour a reduction in technology impact does aid in the reduction of overall impact. An additional check on this *constant behaviour* assumption is however required since increased value and decreased environmental impact per product — efficiency — is only a necessary but insufficient condition for environmental impact reduction at the global level.

Since technology cannot provide the complete solution to the problem and might even aggravate it, the other components — behaviour and population — affecting the impact should always be considered. For the sustainable society an important challenge lies in understanding and steering the mechanisms underlying this trend towards increased individual welfare. One illustrative representation of this dilemma has received a lot of attention in environmental literature; the *tragedy of the commons* in Text-box 1.1. This problem illustrates the conflict between best *individual strategy* and humanity needs with respect to *common property*, i.e. the earth. This conflict of interest forces humanity away from Bentham's goal of *"The greatest good for the greatest number"*[19].

> **Tragedy of the commons**[70]
> Picture a pasture open to all. It is expected that each herdsman will try to keep as many cattle as possible on the commons. Such an arrangement may work reasonably satisfactorily for centuries ... (as) numbers of both man and beast (stay) well below the carrying capacity of the land. Finally, however, comes the day ... of social stability. At this point the inherent logic of the commons remorselessly generates tragedy. As a rational being, each herdsman seeks to maximize his gain. ... This utility has one positive and one negative component. 1) One additional animal generates benefits which are all received by the herdsman, $+1$. 2) the additional overgrazing created by the additional animal is shared by all herdsmen and consequently only a fraction of -1. The rational herdsman hence concludes that he should add this animal, and another, and another ... But this is the conclusion of all herdsmen sharing the commons. Therein is the tragedy. Each man is locked into a system that compels him to increase his herd without limit in a *limited world*.

Text-box 1.1: Tragedy of the commons[70].

In addition to that, the self regulating concept founded on the free market principle — denoted by the "*invisible hand*" seen in economics[170, pp.347] — only appears to force behaviour in the direction envisioned by Bentham when the values and costs are (immediately) apparent or experienced by the actor. For environmental impact the costs might not only affect different actors in different locations, but also after different time periods. Consequently, the impact of an action might not be felt by the actor before a certain time period, hence the incentive to abstain from action is absent, making the free market principle a poor guide to sustainability for humanity.

A closely related phenomenon is an *externality* to an economic transaction; consider a voluntary transaction between two parties A and B. The influence of this action is not limited to these parties, but also affects party C. As an example; consider an airline A who offers a travel product to passenger B, both stakeholders are beneficiaries to the transaction. The flight influences external parties both negatively and positively. The noise produced by the operation of the flight deteriorates the living quality of those affected by it (party C). On the other hand, the airport (party C) benefits from the additional traffic and income generated by the customer in for instance the tax-free area. This influence, external to the voluntary transactions, is captured in the economic concept of *externality*.

Accounting for these externalities, that is introducing their costs in the decision of the actor is one method of correcting the free market. An alternative would be to restrict all possible actions to a set of allowable actions, e.g. by regulation. The former puts the responsibility of the action and its externalities with the actor, whereas the latter puts the responsibility at the government or regulator. More appropriate and tailored methods might exist, but this thesis focusses on appropriate methods of evaluating the impact of technologies. Since both preemptive influences on behaviour require the quantification of the externalities of each action. Furthermore, the preemptive influences are especially required in the "correction" of (novel) technologies, since removing them from society is much more difficult than preventing them from being introduced.

1.1.3 Concluding remarks

Summarizing, sustainability has to deal with the finiteness of earth for indefinite periods of time; finite number of resources, finite space, and the boundaries of the earth system. The consequent boundaries should not be surpassed if subsequent generations are to inherit a habitable earth system. Since two boundaries are already crossed, the anthropogenic impact needs to be reduced, while remaining within the limits set by the other boundaries. Reducing environmental impact requires the treatment of the characteristics of environmental impact as denoted in the right side of Equation 1.1; 1) growing environmental impact despite large technological efforts and 2) absence of central control and the system is composed of multiple decision making elements. These elements dominate the behaviour and consequently the environmental impact and complicate the reduction of the anthropogenic environmental impact.

Despite large efforts to find technical solutions, the problem of impact reduction might be classified as a *"no technical solution problem"*, due to the strong dependence of environmental impact (externalities) on human behaviour[70]. This type of problem is characterized by the fact that technical solutions can only solve parts of the problem. Nevertheless, technology can *aid* in finding and providing solutions even though behaviour is considered dominant. For that purpose, technical solutions, i.e. *doing things right*, need to be guided by additional considerations on behaviour, or *doing the right things*. This political task, where politicians are considered representatives of the people experiencing the externalities, requires the quantification of the impact of externalities. A framework for anthropogenic environmental impact evaluation needs to implement methods addressing the coupled effect of behaviour and technological impact.

> *Both behaviour and technological impact are required in the evaluation of sustainable technologies. This introduces additional design criteria.*

Such a framework, capable of quantifying the impact of externalities, requires the influence of *all* anthropogenic activities on the global boundary parameters. This utopian view is far from achievable[128], due to the complexity of the earth system and lack of knowledge and understanding in the underlying principles of many of its elements as well as their interactions.

1.2 Aviation as a system-of-systems

The continuing growth in environmental impact, despite the strong focus on technology efficiency improvement during its history, makes aviation a challenging area of anthropogenic impact reduction. The issues arising when considering how the bounded earth concept affects the transport system, i.e. which boundaries should be posed on aviation and which limits should be set, are simplified by transferring the bounds from the earth system to the aviation transport system. This implies that an impact budget for aviation has been created, which is a non-trivial task. Aviation has many externalities[84], however in line with ACARE goals[138], *climate change* is taken as a the most important contribution of aviation to anthropogenic impact. In more detail, ACARE devised a vision for 2020[138], in which the air transport system should reduce the environmental impact with respect to the baseline year 2001:

- 50% reduction of carbon dioxide emissions,
- 80% reduction of nitrous oxides, and
- elimination of noise outside the airport boundary, while at the same time
- increasing European competitiveness in aviation.

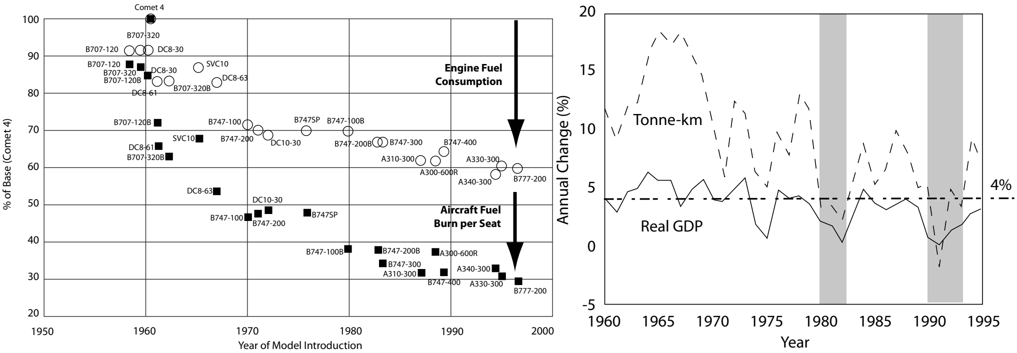
These four goals show the desire for environmental impact reduction at the aviation level, while at the same time remaining competitive. From these drastic reductions in environmental impact it is clear that for the age of sustainable “growth” the required improvements in quality, performance, safety and security and economy, combined with the need for reduced environmental impact and increased safety level, will need a future aircraft system that differs as much from the current aircraft system as the current system differs from that of 1930[187]. Consider for example the difference in aircraft use in the early days of aviation with the current large scale commercial system, and the corresponding changed requirements and issues. A similar change is expected for the novel technologies proposed to cope with the previously identified two challenges

1) growing impact despite technological effort on reducing it,
2) absence of a single entity controlling the behaviour and environmental impact,

To investigate whether these challenges also apply to aviation, both will be substantiated in the following sections.

1.2.1 Historical aviation environmental impact growth

Passenger volumes and transported goods are growing more rapidly in aviation than in the general transportation sector and as a consequence also aviation’s contribution to the environmental impact increases. The European transport sector production of carbon dioxide emissions grew, between 1990 and 2006, with 25%, from 680 to 850 million tons. Within this European transport sector, the aviation production grew in the same period with 56%, from 16 to 25 million tons[53, pp.43]. Although this contribution appears limited, the effect on the environment might be two to five times this value due to the altitude at which these pollutants are emitted. Furthermore, the European sector is considered relatively mature and is easily surpassed in growth by the Asian air transport market. Consequently,



(a) Aircraft emissions reduction by year of introduction. (b) Global passenger growth by year.

Figure 1.3: Comparison of efficiency and travel growth, source: www.grida.no/publications/other/ipcc_sr/

globally, aviation is expected to continue its growth in the future[36, 2] and with it the environmental impact.

In the past, aviation has dealt with its challenges by investing in novel technologies [25, 70]. The same approach is also used towards environmental impact — examples are: silent aircraft initiative, greener by design and CleanSky[2]. The inadequacy of current technology developments in reducing the global aviation environmental impact is illustrated by comparing the increase in efficiency to the increase in passenger growth. As shown in Figure 1.3a, the increase in efficiency of aircraft amounts to an (exponential) average reduction in fuel burn per seat of 4% per year (1960-1990) when considering aircraft technologies at the time of their introduction. The actual percentage for the world fleet is lower, since newly introduced aircraft do not replace the world fleet immediately[33]. Also shown in Figure 1.3b is the annual growth of the passenger kilometers, which has only been lower than these 4% during the oil crises of 1980 and 1990. In the period from 2001 to 2009 the increase in passengers continued at an average rate of 3.7% increasing from 1640 to 2277 million passengers [3]. Furthermore, increases in efficiency in these conventional technologies are becoming increasingly resource intensive, due to technology maturity[183, pp.7]. Even, the expected increase in efficiency — claimed to be 15% by 2015[4] — by the proposed geared turbofan as a new engine option (NEO) on the Airbus A320 NEO for 2015 is considered insufficient to achieve the required reduction in aviation environmental impact. Alternative developments include the Boeing 787 Dreamliner and Bombardier CSeries geared turbofan concepts (GTF). Therefore it must be concluded that further efficiency improvement using conventional technologies[183] and methodologies, with the current and forecasted growth rates of transport needs, is insufficient to reduce aviation environmental impact. This approach, i.e. creating a novel system with a lower environmental impact without regard for behaviour, is also taken by most environmental impact reducing projects focussing on novel technologies and methodologies, e.g. silent aircraft initiative, greener by design, and CleanSky. Especially when considering that the ACARE environmental impact reduction goals are posed at the aviation level, whereas the technological solutions are treated at

---

[2] www.silentaircraft.org, www.greenerbydesign.org.uk, www.cleansky.eu

[3] www.iata.org/pressroom/facts_figures/fact_sheets/Documents/Industry-Facts-Sept-10.pdf

[4] Source: www.airbus.com

the system level[6, 128]. This gap in evaluation might be justified for incremental changes in technology, where the effect on behaviour is limited. However, for the novel technologies proposed to achieve the required reduction in environmental impact, this is considered insufficient. As a consequence the challenge of "impact increase despite large efforts to decrease it" is present in aviation.

1.2.2 Structure of aviation

From the physical point of view aviation system consists of various systems (subsystems): infrastructure, vehicles, equipment, power systems and control communications and location systems[179]. These entities constitute the physical part of the system-of-systems[41]; the resources. Their interaction is complex but appears organized; aircraft are fuelled before take-off, baggage is loaded in the aircraft, aircraft are lined up for departure and transport passengers to various destinations. However, no single entity controls or coordinates all of these physical systems. The lack of overall control classifies aviation as a system-of-systems. DeLaurentis[41] identifies in addition to the resources; economics, operations and policies. These additional categories provide an important different viewpoint, resulting in additional relations between elements within the elements, completing the set of interactions. The behaviour of the system-of-systems is dominated by the structure and organization of the elements as opposed to the characteristics of the basic elements. This becomes even more clear when looking at how aviation is composed of multiple intertwined stakeholders[85]. Where stakeholder will be defined as elaborated in Section 2.2:

> *A stakeholder for aviation is (by definition) any group or individual who can affect (and who itself is impacted by or benefitting from) the achievement of aviation's objectives.*

Using this definition, aviation consists of *operators*, controlling the system, e.g. airlines, airports and air traffic management. These organizations provide the service experienced by the users, using the physical systems comprising aviation. The *operators* are supported by organizations providing (and maintaining) these physical systems, i.e. *manufacturers*. These organizations, ranging from aircraft manufacturers to internet service providers, are not strictly limited to aviation. Furthermore, the operators require finances for their short and long-term goals, as well as support in the valuing of the expensive assets. These *facilitators*, e.g. investors, lessors and aircraft valuation companies, are broader oriented than aviation. Furthermore, aviation has to operate within the regulations set by regulatory agencies and governments, *regulators*, who use legislation and guidelines to locally steer aviation. Finally, the existence of aviation is justified by its end-users, *users*, e.g. passengers and freight forwarders. For an environmental impact evaluation the system-of-systems aviation should consist of *all stakeholders*. As a consequence, the previously discussed "natural" elements in the aviation system should be supplemented by the people and organizations affected by the aviation system-of-systems or elements thereof. This is due to the previously identified — positive or negative — externalities of any (trans)action. This results in lobbying groups trying to exercise control over specific externalities, drawing attention to specific externalities they are trying to influence. However, for a sustainable society also the externalities not being represented by a lobby group should be considered.

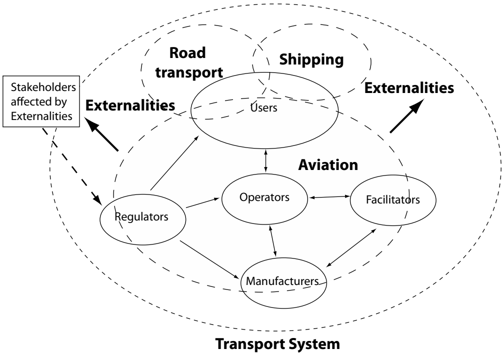


Figure 1.4: Schematic representation of the broader view of aviation. The size of the stakeholder spheres is not to scale.

As indicated, some stakeholders and their influences are not limited to aviation. Consequently, when adopting a higher aggregation level, the system-of-systems compromising aviation cannot be considered the sole provider of transport. Consequently, aviation influences and is influenced by these alternative means of transportation, e.g. road transport and shipping. Aviation should therefore be treated as a system-of-systems within the larger transport system[87], which in itself is part of human society. Due to the large mutual influences, the aviation system cannot be seen as a closed system, but has to be addressed as an open system, where influences from outside aviation affect the behaviour of the stakeholders within it as well as the other way around. The current treatment of aviation as a closed system requires explicitly accounting for these external factors. The previous considerations have been schematically represented in Figure 1.4. The arrows represent direct influences between the elements within aviation, this representation is incomplete but already shows the influence of various stakeholders on each other both within and beyond aviation. Furthermore, the individual stakeholders are spread geographically around the earth. The global features of aviation add to the difficulty in effectively controlling its environmental impact at a regional, national or global level. This is illustrated by the temporary introduction of a carbon-tax by the Dutch government, clarified in Text-box 1.2. Besides illustrating the importance of a transnational policy to level the adverse economic effects for the stakeholders (level playing field), this example illustrates the effect of unanticipated stakeholder behaviour. Its significance requires its consideration in environmental impact evaluations in the framework. This absence of central control presents aviation with the second challenge identified in the first section. This requires a different treatment when designing environmental impact reducing technologies as will be substantiated in Chapter 2.

1.2.3 Design for sustainability

The creation of novel technologies is driven by mutual benefits for customer and manufacturer. This free market is “corrected” for undesirable technologies, i.e. externalities, by legislation. This is illustrated by Figure 1.5, which shows the (incomplete) interaction between the elements in aviation introduced in the Section 1.2.2 and Figure 1.4. No direct

Aviation tax

Due to the many intertwined stakeholders at global level of the aviation system, (national-) governmental control on this system is limited as was demonstrated by the Dutch carbon-dioxide tax policy. The Dutch government introduced a tax on each travel ticket the 1st of July 2008, despite much protest from passenger organizations and airlines. The result was that the number of travellers departing from Dutch soil decreased. However, instead of refraining from travelling as intended, travellers started to depart from German and Belgian airports. This shift resulted in a net increase of the carbon emissions (due to the additional kilometers travelled, by car/train/bus).

The German government announced a similar tax in 2010 for introduction in 2011, after much criticism from airlines, denoting it a tax at the expense of airlines and passengers without environmental benefit.

Text-box 1.2: Dutch and German aviation tax-policies

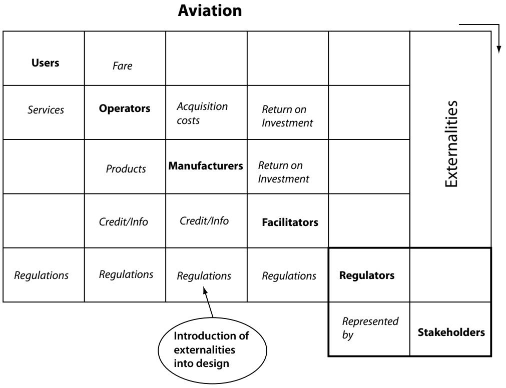


Figure 1.5: Limited view of aviation and its externalities. The current free-market correction on these regulations is through regulations designs have to comply with.

link exists between the manufacturers developing and introducing the design and stakeholders affected by its environmental impact. Incorporating considerations of externalities are limited to the regulations created by the representatives of the stakeholders affected by the technology. Furthermore, this correction on environmental impact occurs after design and introduction of technology, i.e. showing compliance of a system to regulation. The inadequacy of this approach is indicated by the growing environmental impact despite the increasingly strict regulations on environmental impact, e.g. noise and emissions. This post regulatory approach results in the absence of representatives of externalities in the development of a novel technology, e.g. novel aircraft. In aviation, preemptive corrections do exist but are limited to safety. Preemptive in this context means, showing compliance to regulations before starting the development of novel technology. Furthermore, these regulations are posed at the system level while the impact is felt at the system-of-systems level.

Consequently, the current approach of manufacturer-focus on consumers and selling products has proven inadequate for sustainable product development. A complementary view of manufacturer-customer interactions is presented in Buchanan[28, pp.128–129]. Various strategies to design products can be and are used by manufacturers and suppliers: *prey*, *stranger*, *neighbour* and *friend*. The *prey* orientation identifies sellers as being primarily concerned with the exchange process with the lowest possible level of quality. The *stranger* orientation wants to make a sale but is indifferent to the customer's real concerns. The third; *neighbour* orientation invests in the customer relation but is still largely unaware of the customer's lifeworld. Finally, the *friend* view, the orientation is towards a satisfied customer, and is achieved by an engagement with customers, but is rarely seen. On the demand side on the other hand, the behaviour is driven by an ill understood combination of moral, social and economic stimuli. To achieve a sustainable society, a fifth view is proposed; *supervisor*, which not only engages with the customer, but also identifies the *true* needs of current and future customers and all other stakeholders, i.e. addresses the conflict of group and individual need. This even requires suppliers, customers and stakeholders to engage with issues not represented by today's stakeholders. This utopian view is considered an unattainable goal in the current economical system as the additional effort to comply with these additional requirements is not monetised. Nevertheless, a framework for the evaluation of existing and proposed technologies based on current and future requirements, while accounting for behaviour, supports the development of truly sustainable products.

The previous considerations make the external enforcement of environmental impact reducing measures mandatory. In essence incentives, external to the current design process, should steer the behaviour of the manufacturer in the environmental impact reducing direction. Furthermore, effective steering of the design process requires a thorough understanding of the design and optimization of technologies. Effective in this context means, not controlling every aspect of the design process, but limiting control to those elements which determine the technology environmental impact. This latter is especially important since aviation also fulfils an important role in the current society, and trying to eliminate all external effects would effectively mean eliminating aviation instead of finding the appropriate balance between benefits and drawbacks.

1.2.4 Concluding remarks

Aviation will be one of the critical and highly challenged segments within the transportation sector. Despite the focus on technology and resulting impact reductions, similar reductions in environmental impact of aviation are not achieved. Furthermore, no single stakeholder, e.g. organization or corporation, controls all elements compromising the global industry of aviation, preventing an effective environmental impact reduction at a global scale. Even more, the intertwined set of decision making stakeholders affects the behaviour and environmental impact of aviation, making the individual treatment of stakeholders environmental impact inadequate. Consequently, to predict the environmental impact of aviation, the large number of interactions between the stakeholders, of which many interactions are unclear and/or continuously changing, have to be captured. This makes the modelling of the complete aviation system-of-systems a futile task. However, it is considered that by studying elements or simplified relations, depending on the issues considered, improved understanding can be gained[116]. For the environmental impact evaluation both elements and their relations (although limited and simplified) need to be treated simultaneously to arrive at a definitive conclusion about the system-of-systems level environmental impact.

This mandatory inclusion of stakeholders and their interaction for the evaluation of environmental impact, affects the design procedure and introduction of novel technologies directly. To design for environmental impact in a hypothetical "free-market" without legislation to account for externalities results in the inclusion environmental impact considerations only if they are beneficial for elements within aviation, i.e. customers are willing to pay for them. This is undesirable from a sustainable point of view, as pollution is allowed if customers, who might not even be affected by it, are willing to pay for it. The current method of correction by legislation introduces a time lag: aircraft are introduced, aviation changes and once the environmental impact is shown undesirable legislation is adapted for new aircraft designs. As a solution to this, all stakeholders are to be included in the design procedure. This method of preemptive inclusion of the externalities in the design poses a challenge, but has the best chance of reducing environmental impact. The challenge lies in the additional requirements from the stakeholders which have to be considered in aircraft design.

Both issues are coupled, a means of measuring the impact of an element, i.e. design, on the system of systems level is needed to define the desirability of the technology, and the system design affects the predicted environmental impact. To address both issues and facilitate design for reduced environmental impact, methods are required which:

- consistently identify the stakeholders, their needs and interactions
- predict the effect of impact reducing technologies on the interactions between and behaviour of various stakeholders
- incorporate the needs of stakeholders representing externalities.

No single method is available to address all three goals at once. The collection of methods that can, has to be integrated in a single framework, predicting impact of technologies for policy makers to determine whether they are desirable before being implemented in the aviation system.

1.3 Thesis goals

To support the steering of technology, i.e. *doing the right thing*, a framework is devised intended to evaluate the environmental impact of a novel technology at the system-of-systems level. This requires a method which captures the effect of the technology and the associated effect of behaviour within the system-of-systems on the system-of-systems' externalities, i.e. environmental impact.

> *Devise a **method** that couples system level impact and human/ organizational/ societal behaviour to evaluate the true impact of a technology at the system-of-systems level.*

One important component in the system-of-systems is the stakeholder responsible for the development and introduction of novel technologies. In order to effectively and preemptively steer this technology introduction, the process of the manufacturer is to be understood. One of the readily identified difficulties is the prediction of the environmental impact at system level and appropriate management for it during the design. Furthermore,

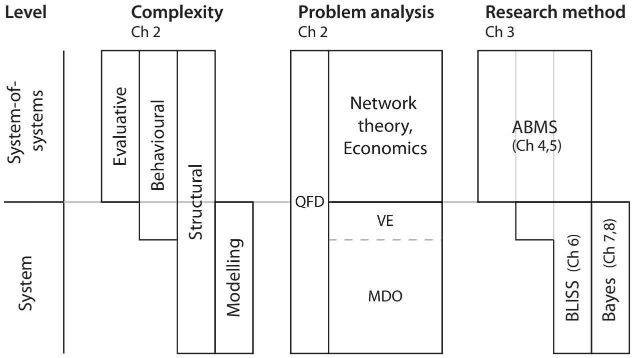


Figure 1.6: Schematic overview of system level, complexity and available and proposed tools addressed in this thesis.

changes in the design become more costly with increasing design maturity[23]. As a consequence the incentives, procedures and uncertainties in the design and development process during the early stages of design are investigated in order to effectively steer the design in the environmental impact reducing direction.

> *Investigate the early stages of design to identify the shortcomings of the current design* ***method*** *in reducing the environmental impact and illustrate this using the variety of proposed technical solutions.*

For this purpose an evaluation framework is devised and its proposed elements are illustrated using various proposed technical solutions; i.e. the MagLev assisted take-off, the Prandtl Plane[64, 146, 147], the Blended Wing Body[104, 191], Propeller aircraft and the Coandă micro aerial vehicle.

Although both goals are closely coupled and should ideally be considered with a single tool, this is considered infeasible. As a consequence, a collection of tools and methods is considered composing a framework which can address both challenges. Creating a framework with a complete set of methods and tools to address the challenges posed by “design for sustainability” is the main focus of this thesis. The show cases used herein illustrate the tools using simplified but realistic technology examples.

1.3.1 Evaluation framework

In order to address both goals, system-of-systems and system level issues have to be tackled. To formalize the treatment of these considerations, systems theory is complemented by complexity theory. Complexity theory and the types of complexities identified are taken as a guide to what the methods and tools have to address if design for sustainability is to become a reality. Complexity is taken as the red thread to the issues which need to be addressed by the methods and tools comprising the framework. The use of the proposed tools is illustrated by simplified but realistic show cases. Schematically the elements of the framework and their implementation are shown in Figure 1.6. The collection of complexities shown in Figure 1.6 is not claimed to be complete, but is limited to the complexities addressed in this thesis. The complexity types and the level they are addressed is illustrated in the column labelled **complexity**. As an example: “structural complexity” is encountered and addressed at the system-of-systems level and the system level, while “behavioural complexity” is encountered at the both levels, but is addressed only partly at the system level. The second column labelled **problem analysis** illustrates the methods used to address the complexities. This column is elaborated in the next paragraph. The final column labelled **research method** illustrates the tools used to address the complexities. Consider the rectangle labelled ABMS, this treats the evaluative, behavioural and structural complexity at system-of-systems level. This is substantiated in the second paragraph. The area covered by the tools corresponds to the complexities and the level they are used for. Furthermore, the chapters in which the appropriate show cases cases can be found are shown by the numbers in brackets. These show cases are introduced in the final paragraph called “illustrative examples”.

1.3.2 Problem analysis

The basis for the framework is chosen to be Quality Function Deployment (QFD) for its focus on the incorporation of customer needs/ wants in the design[35]. To achieve the goal of *true* impact at the system-of-systems level, the QFD basis requires the incorporation of all stakeholders, in particular the ones representing externalities. This is considered a good basis, despite the fact that not all environmental impacts are represented by a stakeholder. This incompleteness is caused by either ignorance of the effects or temporal dispersion of stakeholders, i.e. stakeholder needs do not yet “exists”. Since the focus lies in the quantification of technology induced environmental impact, the optimal method of manufacturer persuasion to actually include all stakeholder needs in the design is a difficult matter left for policy makers. Nevertheless, the multitude of interacting stakeholders and their effect on the environmental impact requires the treatment of the complexities encountered in Complex Large-scale Interconnected Open Socio-technical systems[177] (CLIOS). Properties of such *complex adaptive systems* are treated in Section 2.1. The treatment of the encountered complexities is divided in the system-of-systems and system level. At the system-of-systems level the complexities addressed are *evaluative*, *behavioural* and *structural* and at system level the ones addressed are *behavioural*, *structural* and *modelling* complexity .

The system-of-systems level complexities are treated by an extension of the QFD framework based on a combination of network-, stakeholder identification- and economic-considerations. These considerations are substantiated in Section 2.2. The system level complexities are considered in the QFD framework, but an additional, more quantitative, view is adopted by the value engineering (VE) and multidisciplinary design optimization (MDO) framework as detailed in Sections 2.3 and 2.4. MDO is a computational approach based on the model representations of the real world system. For the novel technologies envisioned to address the sustainable conundrum this introduces unknowns in the design and MDO results. These unknowns are investigated using a probabilistic treatment in order to support the estimation of .

1.3.3 Research methodology

Chapter 3 introduces three tools, labelled ABMS, BLISS and Bayes, to address the complexities at the various levels. A single integrated tool is preferred but infeasible to address all complexities. To achieve tool completeness, the complexity types are taken as a guide.

The agent based simulation environment (ABMS) is addresses the intertwined stakeholder behaviour with respect to system designs and its impact on the technology-environmental-cost. This simulation approach is chosen for its ability to capture the expected non-linearities in the stakeholder interactions. Furthermore, it provides a means of focussing on individual stakeholder behaviour and their interactions. This provides a flexible framework required for the evaluation of the environmental impact. At the system level, the MDO framework is implemented by the chosen Bi-Level Integrated System Synthesis method (BLISS). This computational BLISS framework is largely dependent on the computational models providing the modelling capabilities. Each of these models is an imperfect representation of real system behaviour. The unknown and consequently uncertain errors are introduced in the quantitative computational approach. As a consequence the errors for an incorrect prediction of system behaviour are considered in more detail using a probabilistic approach (Bayes).

1.3.4 Illustrative examples

In order to illustrate the tools proposed in Chapter 3 to address the four complexities, (**E**valuative, **B**ehavioural, **S**tructural and **M**odelling), five simplified but realistic show cases will be discussed and addressed by the appropriate tools. The stakeholders in aviation are identified and characterized in Chapter 4. The MagLev system will be discussed to illustrate the coupling between behaviour, system level impact and emerging behaviour in aviation in Chapter 5. Furthermore, the Prandtl Plane is used to illustrate the occurrence of new strategies and goals after the introduction of a novel technology. Chapter 6 discusses the implementation of the Blended-Wing-Body in the BLISS MDO framework. Finally Chapters 7 and 8 discuss the complexity of modelling system behaviour, using the conventional technology of propeller propulsion considered to reduce the environmental impact and the novel technology of a Coandă Micro Aerial Vehicle (MAV) as illustrative examples.

Chapter 2. Problem analysis

> *"Scientists investigate that which already is; Engineers create that which has never been."*
> Albert Einstein.
>
> *"Science is the study of what Is, Engineering builds what Will Be."*
> Theodore von Karman.

The previous chapter showed the inadequacy of aviation to reduce environmental impact when left to its own resources. To facilitate a reduction of aviation environmental impact, two goals were introduced:

1) Devise a method that couples system level impact and human/ organizational/ societal behaviour to evaluate the true impact of a technology at the system-of-systems level.
2) Investigate the early stages of design to identify the shortcomings of the current design method in reducing the environmental impact and illustrate this using the variety of proposed technical solutions.

The first goal requires the evaluation of environmental impact at aviation level to facilitate preemptive steering of technologies towards a reduction of environmental impact The second goal facilitates investigating of the design procedure to effectively steer and facilitate the development of novel technologies for a reduction of environmental impact at the system-of-systems level. In particular the lack of central control complicates the achievement of these two goals. This limited control mandates analysing the effect of changes on aviation by incorporating the stakeholders as well as their interactions. The previously discussed difference in stakeholder and system-of-systems behaviour is called emerging behaviour:

> *Emerging behaviour is system behaviour which is not a property of any of the (interconnected) elements of the (complex) system, but is still a feature of the system.*

"System" is either system or system-of-systems depending on the context. To be able to address this *emerging behaviour* more formally, the complexities present in CLIOS[177] at

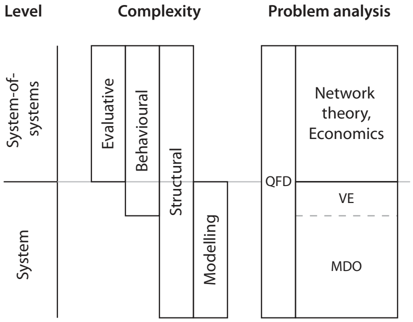


Figure 2.1: Schematic overview of system level, complexity and available and proposed tools addressed in this thesis.

two system levels are used as a starting point. These complexities are shown in Figure 2.1 in the column labelled complexity. The problem defined by the two goals and complexity types is addressed using the tools denoted in the column labelled problem analysis. These tools span the system to system-of-systems level as required by the framework.

The environmental impact of a technology in this complex system-of-systems is determined by this emerging stakeholder behaviour. As a consequence, the stakeholders as well as their interactions, causing the emergence, are to be included in the design. This requires the identification and translation of the *true needs* into the technology design. True needs are considered in contrast to market segmentation, e.g. finding the pocket of latent demand containing enough buyers willing to pay a price that suits the seller's/designer's aims. This product development viewpoint only identifies the (sum of the) individual needs or the needs of a segment of society, which are shown to conflict with the environmental needs.

In response to these needs, whether sustainable or not, a product is to be developed. Aircraft manufacturers employ systems engineering to organise and control their product development programmes. The set of methods and "language" provided by systems engineering is used to address the complexities encountered in the product development process. Environmental impact reduction introduces additional challenges in the development process for which additional methods and tools are needed. To incorporate the *true needs* of the stakeholders, Quality Function Deployment is taken and extended from the *customer* and *natural stakeholder* orientation to accommodate the needs of multiple interconnected *true* stakeholders. As a result the product development process is no longer limited to the system, i.e. aircraft, but to the system-of-systems, i.e. aviation. To address this complexity, a supplemental view on the technology design is adopted to support the increasingly interconnected proposed solutions for environmental impact reduction. Besides the more complex requirements derivation, the technical solutions are becoming more coupled to benefit from synergy. This makes the design process more complex. To address this complexity an additional view is adopted using value engineering (VE) and multidisciplinary design and optimization (MDO). To provide insight in the sources for the uncertainty in the unknown errors introduced by the model representation of the real system in the MDO approach a probabilistic framework based on Bayes is used.

2.1 Complexity perspective

Aviation has been characterized as a Complex Large-scale Interconnected Open Socio-technical (CLIOS) system. Complexity is therefore considered a suitable guide addressing the environmental impact issues in such systems. Before continuing with the treatment of the environmental impact of such systems, it is therefore justified to consider the properties of CLIOS systems more closely. Various definitions of complex systems exist depending on the field they are derived from. Sussmann[177] defines a CLIOS system as;

> *A system is complex when it is composed of a group of interrelated units (component and subsystems) for which the degree and nature of relationships is imperfectly known, with varying directionality, magnitude and time scales of interactions*

Furthermore, Mitchell[119, pp.13] proposes as a definition of a complex system

> *A system in which large networks of components with no central control and simple rules of operation give rise to complex collective behaviour, sophisticated information processing and adaptation via learning or evolution.*

with the additional note that sometimes the term adaptive is added if the focus lies on the adaptiveness of the system. Finally, Miller[116, pp.9] identifies as a criterion for complex adaptive systems

> *Complexity is a deep property of a system, ... A complex system dies when a (critical) element is removed, but complicated ones continue to live on, albeit slightly compromised.*

Although all three views highlight different aspects of complex systems, they share the notion that the complex system should be treated as a whole, consequently challenging the reducibility usually employed in system analysis and engineering. This reducibility is based on the notion that all system behaviour can be understood by studying the behaviour of the elements. Furthermore, all three definitions point to the sensitivity of the system behaviour and importance of interactions between the elements and apparent organization despite the absence of overall control. These elements are considered essential to complex systems.

2.1.1 Properties of complex adaptive systems

In general, complexity science is a field that focuses on the universal principles common to all systems. In particular, how ‘bottom up” principles, result in adaptation and emergence. This emergence or self-organization appears to contradict the second law of thermodynamics; “the entropy of an isolated system, i.e. chaos/disorder, can never decrease”[134, pp.46]. This property of self-organization without overall coordination, denoted by Smith[170] as the “*invisible hand*”, has been studied by Holland[76, 134]. Holland identified that the properties of complex (adapative) systems include; *aggregation*, *nonlinearity*, *flows* and *element diversity*. Furthermore, the common mechanics of complex systems include *tagging*, *internal models* and *building blocks*. *Aggregation* allows, for example, grouping of individual airlines into a meta-airline due to a sharing of the common trait of transporting passengers through the air. These aggregates can portray different and adaptive behaviour. That is, airlines might merge, new ones might emerge and others might go bankrupt and disappear. Despite all this the aggregate of airlines continues to transport passengers. Finally, these aggregates continuously adapt and portray *nonlinear* behaviour. Various *flows* can be identified depending of the problem of interest, e.g. money, passengers and energy. Finally the continuous improvement of service causes each airline to be slightly different resulting in *element diversity*. This diversity is also apparent within aviation by the various brands provided by the airlines, these *tags* direct the behaviour of the passengers to manipulate the symmetries of providing a flight from A to B. That is the characteristics of the airline brand, e.g. name, safety, are visible within the system and directly influences the behaviour of other elements in aviation. In response, each passenger has an *internal model* to decide for a product, where the products are interpreted based on interesting characteristics or *building blocks*. The elements have to be considered and addressed when modelling the system-of-systems behaviour.

Controlling the complete system-of-systems is unfeasible, but steering is possible if the operation of the elements is clear. The system-of-systems of aviation and the elements comprising it are in a constant state of flux as human intelligence continually adapts to address new challenges. Addressing the ever changing state of the system-of-systems and its elements will be a large challenge any method of modelling aviation has to deal with. Furthermore, the resulting insights are likely to affect the system behaviour as they will be used by humans. To address the sustainability conundrum using technology, the existence of flows within the system-of-systems provides a means of affecting the complete system-of-systems by controlling or steering a single element. The resulting behaviour to such an adaptation, e.g. introduction of a novel technology, is *emerging behaviour*. This emerging behaviour, if properly understood, might provide the key to a sustainable technology and subsequently a sustainable society. The importance of these flows draws attention to the interaction between the various elements in complex adaptive systems. The topology of stakeholders and their respective stakeholders can be visualized in a network. These networks and their characteristics are studied by network theory. Network theory focusses on the relationships between entities rather than the entities themselves. The main focus is on how networks arise and evolve. The understanding of these networks could have a large influence on the understanding of social systems[119, pp.233] and their associated environmental impact. As an example; the introduction of a novel aircraft on a route might change airline behaviour on that route, which might enforce other airlines also operating on that route to change behaviour, which might induce behavioural changes on other routes and so forth.

In open literature, the characteristics of two networks have been studied with particular interest: small world networks, and scale-free networks. Small world networks exhibit the property that a small number of random connections, can have a large effect on the connectedness of an originally regular network[192]. Scale free networks[10, 43] show tremendous resilience to random deletion of nodes[119, pp.245]. This is caused by the larger presence of less connected nodes, whereas the properties with respect to information transfer are determined by the few highly connected nodes. The first type shows that relatively small changes to the network might have a significant effect on the distribution of the technologies. The second type shows required focus on large connected nodes to spread ideas. Consequently, changes occur in both element behaviour as well as in structure. The structure and behaviour of aviation are yet to be determined. However, it is clear that for a successful evaluation of the system-of-systems environmental impact, the effect of the — adapting — structure of aviation and its emerging behaviour should be taken into account[43].

2.1.2 Aviation as a complex system-of-systems

A large part of the complexity in aviation originates from the large number of different intertwined stakeholders, all with their own goals and behaviour, resulting in many — unknown — interactions and influences. These effects need to be considered when evaluating technology impact at aviation level, based on the system level impact. Furthermore, this complexity results in the sensitivity of the aviation system to small changes, e.g. novel technology, in particular when considering future states[25]. As a consequence, aviation has to be addressed as a *complex adaptive system*[179, 49], which might change due to the introduction of a novel technology. Donohue[49] even argues that increasing US aviation capacity without compromising safety, will only be overcome by a combination of technology, procedural and regulatory change, driven by economic incentives. This is even more the case for the environmental impact of aviation, which, like safety, is a system-of-systems wide property. Therefore, the technology evaluation framework, needs to incorporate effects from elements beyond the sphere of control (and even beyond the sphere of influence) of the stakeholder directly influenced by the technology. This represents, for example, the effect of the limited influence of the design team within the company, but also the limited company influence on its environment, e.g. passenger flows, regulations and gross national product. Furthermore, this framework should incorporate and emulate the behaviour of *all* stakeholders of aviation, which is far from trivial[69]. As a consequence, complexities are expected at both system levels, which should be addressed appropriately. In line with Sussman[177], the complexities in CLIOS are taken and applied to aviation.

System-of-systems level At the system-of-systems level, *behavioural*, *structural* and *evaluative complexity*[177] are identified. *Behavioural* complexity arises from the fact that the exact impact of an external or internal disturbance on the system is hard to model or predict with accuracy. In particular the emerging behaviour due to the interaction of sets of components. *Structural* complexity is related to the number of components and the interconnections between them. Complexity rises when more elements or connections exist in a system. *Evaluative* complexity arises from the existence of many different stakeholders with different viewpoints about system performance — goals and behaviour — making it difficult to reach consensus on the system design. With respect to managing the physical system Sussman[177] also identifies *nested complexity*, which is complexity arising from the introduction of complex physical systems into the existing institutional sphere. With respect to the evaluation of novel technologies this typically results in an uneven “playing field”, at the disadvantage of the novel technology. This is caused by the fact that the institutional sphere is formed and optimized for existing technologies. As an example, the airline operations, the airport infrastructure and the fuel infrastructure is optimized for the conventional kerosene aircraft. To even this playing field, it is assumed that the point of consideration is sufficiently far ahead in time so the institutional sphere can be adapted to accommodate either technology. The resulting influence of the current institutional sphere is thus assumed negligible.

System level At the system level, the system, e.g. aircraft, should be designed fulfilling the requirements and complying to the constraints. Due to the indication that conventional means are likely to be insufficient in achieving the sustainability criteria[183], additional complexity is introduced into the design process as well, i.e. *structural complexity* and *modelling complexity*. *Structural* complexity, again arises from the large number of interconnected subsystems, components and elements compromising the system and *modelling* complexity arises from the fact that the validity of the results, produced by first principle and high fidelity tools, remains uncertain for novel and unconventional configurations. Both complexities directly influence the predicted behaviour of the overall system and contribute to the *behavioural* complexity.

2.1.3 Measures of complexity

The methods which will be proposed to address the complexity types and the tools to implement these methods are illustrated using show cases. In order to determine how representative the show cases are with respect to the real world environment, the design complexity metrics as proposed by Summers and Shah[176] are used. Three complementary measures are introduced, complexity as size, complexity as coupling and complexity as solvability. Although Summers and Shah propose measures for product, process and problem complexity, this thesis focusses on the methods and tools and hence the problem complexity measures are used. The size complexity is based on entropy and captures the information content contained within the representation.

$$Cx_{size} = M^0 C^0 \ln |idv + ddv + dr + mg|, \tag{2.1}$$

where idv are the variables controllable by the designer, ddv the variables not directly controlled by the designer, dr relations and constraints that dictate the association between other design variables and mg variables that determine how well the current design configuration meets the design goals. In addition to this M^0, C^0 are the number of primitive modules and number of relationships in a certain representation. The coupling complexity is based on the decomposability of the problem Finally, the solvability complexity measures the effort required to solve the problem at hand. Summers and Shah consider the degrees of freedom as the measure for solvability complexity;

$$Cx_{solvability} = \sum DOF(idv) + \sum DOF(ddv) + \sum DOF(mg) - \sum DOF(dr), \tag{2.2}$$

where the variable names are as previously discussed. Since the show cases illustrated are simplified to obtain a solvable problem, the size complexity is taken as the inter problem measure of complexity.

2.2 Quality Function Deployment

Incorporating the needs of the multitude of stakeholders into the design of for instance an aircraft, requires addressing evaluative and structural complexity. This becomes even more complicated when additional stakeholders representing externalities are to be incorporated. The inclusion of these needs in the design is not self-evident, since manufacturers are not able to monetise a reduction in externality. The varied and conflicting needs have to be balanced and treated in a single consistent framework, which couples the impact — system-of-systems level — to the technical solution — system level.

Systems engineering is used by aircraft manufacturers to organise and control the product development process. To support this process, systems engineering provides an interdisciplinary set of techniques and tools to manage complex projects to design and maintain products for their life-cycle[23]. From this systems engineering toolbox Quality Function Deployment (QFD), the structured method of product planning and development, is used as a starting point. QFD provides a set of tools and visual aids for the identification, representation and trace of the relation between customer wants/ needs and the product characteristics during the design[35]. This tool bridges the gap between the customer needs and the proposed technical solutions and is to be extended to address the *true* needs of *all* stakeholders. The approach taken by "conventional" QFD, its abilities and short-comings for environmental impact treatment are discussed first. For the identified short-comings in *true* need identification and incorporation a solution is proposed using a combination of network, social and economic considerations. In support of this, stakeholder identification and salience is used as an indication of the natural incorporation of stakeholder needs by manufacturers and the resulting inability of technology in the current economic system to resolve the environmental impact issue. As a consequence, external incentives, e.g. regulations, are required to incorporate the needs of *all* stakeholders. This will be discussed in the second section.

2.2.1 Conventional QFD

The most important visual aid in QFD is the house of quality (HOQ), which is shown schematically in Figure 2.2. The *whats* capture the qualitative voice of the customer (VOC) and is an ordered hierarchical list of the customer needs. This qualitative voice is quantified in the *planning* matrix, which addresses currently available products and corresponding customer satisfaction to obtain a strategic view of the needs to be satisfied by the new design. The top part, the *hows*, represents the technical response to these needs, and compromises a high level technical description of the planned service. The roof of the house, the *technical correlations*, identifies the relationships between the technical responses. The *relationships* denote the (subjective) relation strengths between the customer needs and the technical solutions represented by technical performance measures (TPM). This matrix can be used to verify if all needs have been addressed by technical solutions and vice versa, if all technical solutions serve a customer need. Finally, the *technical matrix* captures a ranking of technical responses and technical performance targets, based on customer needs and comparisons with competitor products/services. This technical matrix can be used as a starting point for a more detailed house of quality, where it becomes the whats, for further decomposition and/or specification of the product. A limited set from this technical matrix can also be used for another more detailed house of quality, showing decomposition. This sequence of houses of quality allows for a trace of requirements from the actual customer needs (top) to the detail design level (bottom). One of these decomposition steps is schematically shown in Figure 2.3. Tracing back this linked topology of HOQ allows for integration and consequently treats structural complexity at the system level.

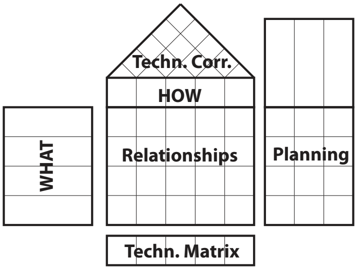


Figure 2.2: Elements in the original house of quality (HOQ)[35].

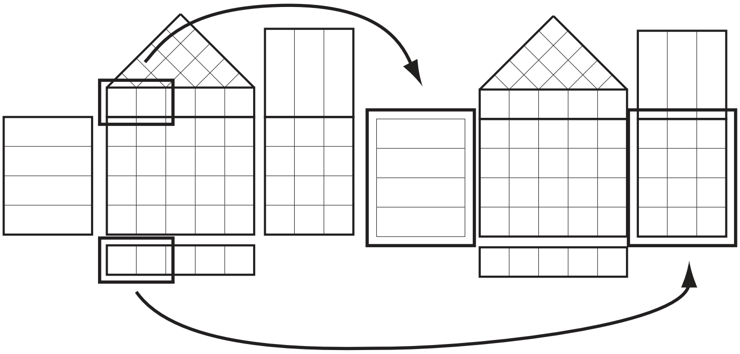


Figure 2.3: Decomposition of the technical solution using QFD[35].

2.2.2 QFD for multiple coupled stakeholders

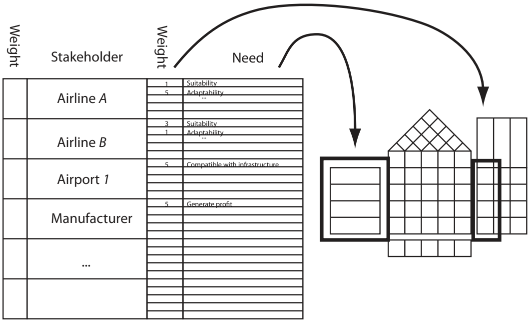
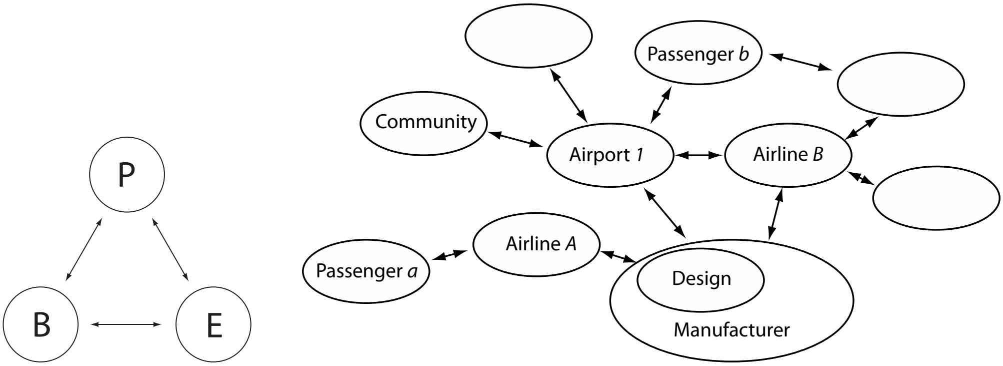


Figure 2.4: Original HOQ for multiple stakeholder needs

One limitation on QFD is the approach for the inclusion of multiple stakeholder needs. This is currently based on the designer's rating of the relative importance of the considered stakeholders. This will most likely result in a rating based on the strategy of the company (e.g. profit, market share). Furthermore, this classification of stakeholder is based on dyadic ties, i.e. two-sided interaction, whereas Rowley argues that this view is too



(a) Mutual interactions[9] (b) Social network including design

Figure 2.5: Cognitive and social network model.

limited for the multi-interacting stakeholder influences[156]. The current multi-stakeholder approach is schematically shown in Figure 2.4. This approach permits inconsistencies between the various stakeholders — willingly or unwillingly — resulting in an incorrect perception of the customer environment and the resulting product requirements. Furthermore, it is based on the "natural" stakeholders, that is the stakeholders that already have an influence on the design, which generally does not include the people experiencing the externalities. In particular for steering the design towards less environmental cost this coupling is important in complex adaptive systems. For this section the focus will remain on incorporating multiple coupled stakeholders in the design.

To extend the QFD framework, the elements in the system-of-systems influencing the needs and desires of the customer are investigated in more detail. From the point of view of the social sciences, the behaviour (**B**) — e.g. purchase of the product — is influenced by characteristics and internal model of the customer (**P**) as well as his/her environment (**E**) (Figure 2.5a). As an example; increased environmental awareness, and resulting legislation (E) might have an effect on the internal model of the customer (P) resulting in a changed perception of the available products and consequently the choice for a product changes (B). All three have a mutual interaction as identified by Bandura[9]. As a consequence, the extended QFD framework needs to include or account for this interaction. The environment can be decomposed into stakeholders, with their own internal properties, values and behaviour, with which they influence the intended customer. The customer on the other hand has an influence on his/her surroundings as well.

Focussing on the social relations between customer and environment, the environment can be considered to consist of stakeholders, e.g. passengers, airlines and airports, schematically depicted in Figure 2.5b. These stakeholders have stakeholders as well. Consequently identifying the stakeholders' stakeholders is a cumulative procedure. This procedure provides a structure beyond the dyadic ties by including the influence of stakeholders onto each other as well as the interaction of stakeholders on the design. This iterative procedure however requires engagement of the manufacturer with the stakeholders to obtain a thorough understanding of their stakeholders needs[1].

---

[1] This might be limited by classified or privacy information when other companies are considered. Value chain

The resulting network of influences can be represented by a network of nodes and connections (Sociogram) or a matrix[164, pp 11.]. Representing this network in a matrix form allows for a consistent identification of the presence or absence of interactions. The *E* stands for the unidentified part of the environment, *Pa* denotes the passenger, *Al* the airline, *Am* the manufacturer of the aircraft. This incomplete set of stakeholders is presented on the diagonal and their interactions, presented off-diagonal, show the connected nature of the stakeholder needs.

The extension to the house of quality, including the interactions between stakeholders, is schematically represented in Figure 2.6. Basically the list of needs representing the original voice of the customer (VOC) is replaced by a matrix, which includes the interactions between stakeholders off-diagonal. The individual stakeholder needs are still rated by the individual stakeholders in the right column. In addition to this the origin and influences on these identified needs are to be determined and visualized. This focusses on the interdependencies between the stakeholders and their needs. The needs and technical solutions directly affecting the proposed design are to be implemented in the voice of the customer column, which is equal to the original HOQ. However, now it not only includes information from the stakeholders needs directly but also how these affect each other. As an example, the airline need for an aircraft is determined by the operation of this aircraft. However, this operation is driven by the passenger need to travel. If this travel need disappears so does the need for the aircraft. This is an extreme case, but alternatives, like the need for local airport compatibility can be driven by the over-constrained hub airports. If the aircraft is to be designed for sustainability, this interdependency is even more pronounced. The need for a low emission aircraft only emerges due to the success of air transportation and the resulting system-of-systems environmental impact.

The most basic form of representing need interdependency is a matrix with stakeholders on the diagonal and signs of the existence of an interaction off-diagonal ($B1, B2, B3$). Here the signs represent whether fulfilling a certain need for a stakeholder positively or negatively affects fulfilling the need of the other stakeholder. In the most extensive form the off-diagonal terms are HOQs themselves denoting the needs from one stakeholder and the (technical) solution provided in that interaction.

By identifying all the needs and interactions between stakeholders, the interaction between design changes onto the desirability for the stakeholders are traceable. The voice of the customer is consequently not merely a statement of the needs, but a statement of the needs and their dependencies in aviation. This allows tracing the effect of changes in stakeholder behaviour and needs through the network onto the resulting needs of the design represented by the VOC. This will be discussed in more detail in Chapter 4.

2.2.3 Stakeholder identification

Mapping the stakeholders and their interactions in this framework provides a qualitative insight in the effect of interactions on their needs. Additionally, it provides a first step in the treatment of the structural and evaluative complexity at the system-of-systems level. Nevertheless, there still is a difference in stakeholders which *are* included in the design and the ones which *should be* included. A clear definition of a stakeholder is given by

---

principles might aid in this respect.

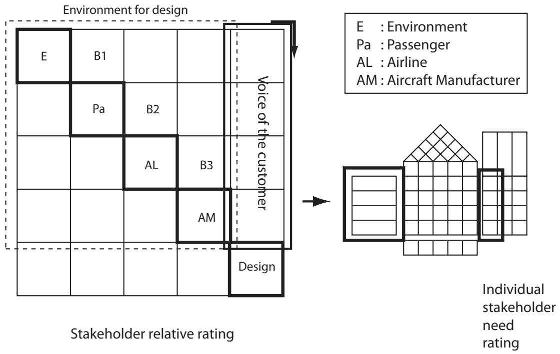


Figure 2.6: House of quality including stakeholder interactions.

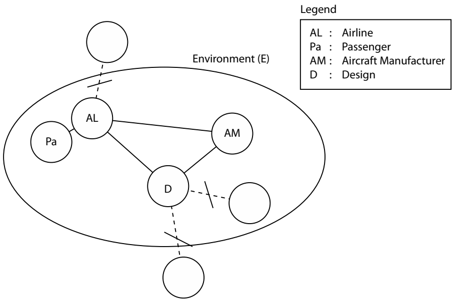


Figure 2.7: Stakeholders of the design project (D). Solid lines representing connections which are included in the decisions on the design.

Freeman[120]

> *A stakeholder in an organization is (by definition) any group or individual who can affect or is affected by the achievement of the organizations objectives.*

The organization in this context is the design team developing the aircraft. This definition is too broad to use for a design as it would involve too many stakeholders which are to be addressed as aviation is a global industry. Nevertheless, the current set of stakeholders is too limited as described in the next paragraph. Consequently an alternative definition for a stakeholder, including the ones affected by the externalities, is proposed in the final paragraph.

Natural stakeholders For the identification of stakeholders, who's needs are already incorporated, i.e. *natural* stakeholders, the classification, or *salience*, of stakeholders proposed by Mitchell can be employed[120]. Three attributes of the relation are considered to be decisive in considering the needs of that particular stakeholder; 1) Power, 2) Legitimacy and 3) Urgency. If an increasing amount of the previously identified attributes is held by the stakeholder, an — natural — incorporation of their needs into the design becomes more likely. This is shown in Figure 2.8. *Power* is defined as the ability of party A to force

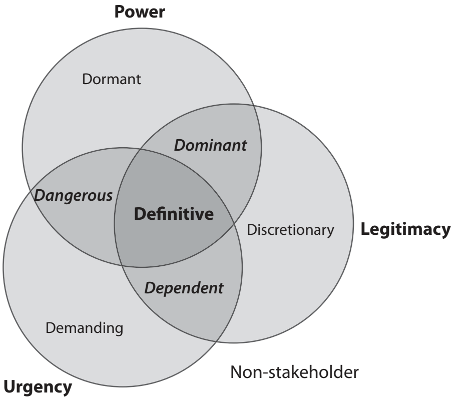


Figure 2.8: Stakeholder salience, adapted from Mitchell[120].

party B into doing what A desires, whether it is in the best interest of B or not. In case of a product, this can be seen as the customer power over the choice for a product, and the manufacturer power over its development. In case of a sustainable design, the customer should perceive value in the product otherwise it will not be purchased (not considering external factors, e.g. legislation). That is, the willingness of the transaction has to be mutual. For externalities this is not the case, since there is no direct mechanism available to reduce or avoid the adverse effects of a transaction. *Legitimacy* on the other hand is a global/national property, defined by the moral of the society. However, due to the less stringent methods of implementing this during design, these goals generally are abandoned first when targets need to be met.*Urgency* is considered the perceived term on which the needs/wants have to be addressed. This is considered an issue related to the choice for product development, e.g. which product should be developed, or to the addressing of the immediate needs of stakeholders during the course of the design. The effect of urgency can be seen when considering environmental impact on the political agenda in the western world pre and post the 2009 financial crisis. The disappearance of sustainability from the political agenda can be interpreted as low urgency. Consequently, sustainability is still perceived as a luxury problem. In particular the time lag between action and effect makes it susceptible to reduced sense of urgency.

True stakeholders To include the people affected by aviation is the stakeholders consulted in the design is larger than the natural stakeholders previously identified. For a global system like aviation the stakeholders of a design should be interpreted as a large part of humanity. This includes, but is not limited to, 6+ billion people, corporations and organizations. To get a feel for the number of stakeholders involved: the amount of primary contractors of Airbus[2] is larger than 1500, Boeing is expected to have a similar amount, the number of their customers, e.g. airlines and lease companies, surpasses 200[3], and the number of annual passengers has surpassed 5 billion in 2010. Identifying *all* individual stakeholders and quantifying their relations is a daunting task, either due to the amount of stakeholders or due to the fact that stakeholders themselves might be unaware of some in-

---

[2] source: http://www.airbus.com/en/airbusfor/suppliers

[3] source: http://www.iata.org/membership/Pages/airline_members_list.aspx

fluences. Furthermore, identifying all stakeholders and their needs is impossible as future stakeholders might be unknown at the time of inference but have to be accounted for in relation to the environmental impact. Consulting each and every stakeholder would require a tremendous amount of resources. As a result the definition of stakeholders as identified by Freeman is too broad to be workable. As a result, a selection of relevant stakeholders has to be made. This selection of stakeholders is problem dependent and no universal decomposition is considered to exist.

Incorporated stakeholders The assumption on which the remainder of this thesis is founded is that politicians force the incorporation of these *true* stakeholders needs in the future. As a consequence aircraft development programmes have to incorporate these needs in the design of their aircraft. The definition of a stakeholder adopted in this thesis is therefore

> *A stakeholder for the aircraft technology development programme is (by definition) any group or individual who can affect the achievement of the programme's objectives*

this is a narrower and more realistic definition of the incorporation of the *true* stakeholder needs. On a side note, the future stakeholders needs as well as the environmental impact not represented by any stakeholder will not be incorporated in the design. As a consequence, this already difficult incorporation of *all* stakeholders is still limited in achieving sustainable technologies.

2.3 Value engineering

The focus of Value Engineering (VE) lies in the selection of the most optimal solution domain and requires the translation of the qualitative needs into quantitative objectives and requirements. Value in VE is determined by the customer. In order to find an appropriate mathematical measure to trade-off proposed solutions this stakeholder need, already present in QFD, is taken as the starting point. The link between QFD/HOQ and MDO provided by VE is shown in Figure 2.9. The stakeholder needs and their relative importance are presented in the right hand side of the HOQ (I). To represent these needs in the product technical performance measures and their correlation are chosen in the upper part of the HOQ (II). The combination results in target values for the novel design (III). The translation of the needs into target values is non-unique and dependent on the technical performance measures (TPM) and consequently the technology being considered. On the other hand, to address the optimization problem by the computational MDO approach the problem is to be translated into a set of design variables, an objective function and constraints (**B**). Also this translation is non-unique and dependent on the technology being considered within the MDO framework, e.g. BWB, PP or conventional aircraft. Consequently, B is different for each of the technology domains (1,2,3). This translation from HOQ (multiple technology domains) into a MDO formulation (single technology domain (1,2,3)) is addressed by VE. Value engineering is used to identify the value adding product aspects, where value is defined by the stakeholder and represented by a single quantifiable measure which provides a comparison between technology domains. The remainder

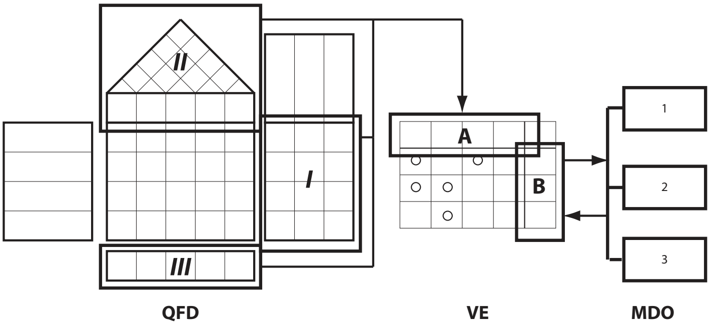


Figure 2.9: Translation of the stakeholder needs into a MDO formulation using VE.

of the stakeholder needs are represented by constraints and the considered technology provides the design variables. Hence VE not only provides the MDO approach with the mathematical problem to be addressed, but also provides an inter-solution measure of desirability.

The measure to compare solution domains is denoted *value*, and is composed of both the benefits of the solution as well as the costs. Consequently, VE can be characterized according to Crum[37]:

> *Value engineering is defined as a disciplined procedure directed toward the achievement of necessary functions for minimum cost without detriment to quality, reliability, performance or delivery.*

The four measures are defined as:

- Quality: the totality of features and characteristics of a product or service that bears its ability to satisfy stated or implied needs.
- Reliability: the ability of the system to consistently perform its intended or required function, on demand and without degradation or failure.
- Performance: the accomplishment of a given task measured against preset known standards of accuracy, completeness, cost, and speed.
- Delivery: formal and voluntary transfer of possession by actual (physical) delivery (within time required by the customer)

where it becomes immediately clear that the customer receiving the product is the one determining how valuable a product is. Consequently, VE engineering focusses on the *product value* for the customer which is different (but does affect) *company value*. VE compares solution domains, e.g. BWB, PP or conventional aircraft, in order to find the optimal domain. MDO searches within a solution domain for the most optimal sizing of the product. This solution domain optimality is determined by the chosen value measure. This value depends on customer satisfaction, in terms of quality, reliability and price[37]. As argued from the systems engineering point of view, the product should fulfil a function, this is termed *use value*. Furthermore, it should look pleasing[144], i.e. *esteem value*. Trade in values are often important, especially in durable goods, i.e. *exchange value*. Finally the *cost value* which is internal to the manufacturer and captures the costs for producing the product.

The focus of the remainder of this section will be on the identification of appropriate measures for *value* and how they are influenced by the design and stakeholder needs. In order to determine the value of a technical solution, the requirements and constraints need to be translated from the qualitative QFD framework, involving non-unique scales into a unique and quantitative formulation suited for a Multidisciplinary Design Optimization (MDO) framework. Furthermore, the dependency of value on the uncertain stakeholder needs results in a coupling between value and stakeholder behaviour. Consider the value increase of operational freedom obtained by the twin-engine Boeing 767 when it received ETOPS clearance. This was not known at the time of development of this aircraft.

In general, the design is performed by a manufacturer and part of a larger programme. The design objective and performance, that is the fulfilment of the stakeholder needs and wants by the system, is only one element in the overall project performance. This dependence on program objectives places additional requirements and restrictions on the design. Overall project performance — part of which is product/ design performance — can be measured in the (potential) revenue of the project minus the cost, possibly discounted for the devaluation of money over time. One measure which can be used is the project Net Present Value[109, 142]. This measure provides a means to quantify the needs of the manufacturer, i.e. increasing the revenue for minimum costs, accounting for the expected future demand for the product. The revenue can be influenced — e.g. product performance — but not controlled by the manufacturer, whereas the costs are largely within the manufacturer's control. In this definition cost means the monetary value of designing, producing and maintaining the product and is therefore different from the cost of the environmental impact[4] [39]. Consequently this issue is aggravated for sustainable design, where both elements of value — benefits and environmental costs — are related directly to the (unknown) stakeholder behaviour. How to implement this in the design procedure is discussed in the second section.

2.3.1 Formulation of the MDO problem

The MDO framework requires a well defined mathematical formulation, characterized by 1) objective function, 2) constraints, and 3) a technical solution characterized by design dependent parameters (DDP). This problem of selecting the best solution space is addressed by VE. However, the mathematical formulation is also dependent on the chosen solution space due to the DDP. In mathematical form, finding the optimal design for these requirements can be written as the search for a set of design variables $\boldsymbol{x}_D$ minimizing an objective $\phi(\boldsymbol{x}_D, \boldsymbol{x}_E)$, while satisfying constraints $g(\boldsymbol{x}_D, \boldsymbol{x}_E)$,

$$\begin{aligned} \min_{\boldsymbol{x}_D} \quad & \phi(\boldsymbol{x}_D, \boldsymbol{x}_E(\boldsymbol{x}_D)) \\ s.t. \quad & \\ & \boldsymbol{g}(\boldsymbol{x}_D, \boldsymbol{x}_E(\boldsymbol{x}_D)) \leq 0 \\ & \boldsymbol{x}_{D,lb} \leq \boldsymbol{x}_D \leq \boldsymbol{x}_{D,ub} \end{aligned} \tag{2.3}$$

---

[4] Although attempts have been and are made to quantify environmental impacts in economic terms, www.se2009.eu/en/meetings_news/2009/9/8/pavan_sukhdev_wants_to_put_a_price_on_nature

$\boldsymbol{x}_D$ is the set of parameters controllable by the designer or manufacturer, i.e. DDP, and $\boldsymbol{x}_E(\boldsymbol{x}_D)$ other uncontrollable influences, which can be stakeholder behaviour or physical influences[23]. Solving Equation 2.3 is left for MDO discussed in Section 2.4, however which formulation should be addressed, i.e. which objective function, which constraints is determined by value engineering and the chosen value.

Value is mathematically defined as the ratio between function and cost. The value of a design is difficult to identify, due to its dependence on function which is based on non-uniformity in the stakeholder needs. As an example; the combination of payload increase, measured in volume, and reduction in costs, measured in monetary units, and increase in range, measured in kilometers, into one objective function is non-trivial. Consider the often used method of weighted linear combination,

$$\begin{aligned} V = \phi &= w_1 \frac{P}{P_{ref}} - w_2 \frac{C}{C_{ref}} + w_3 \frac{R}{R_{ref}} \\ \sum_i w_i &= 1 \end{aligned} \tag{2.4}$$

where V represents the objective function, and w_i the importance weights of each of the needs, translated into technical performance measures (TPM). These weights are particularly important when balancing needs, since a larger range and payload volume in combination with a cheaper aircraft is always desirable. Despite the undetermined weights, this approach allows for a mathematical treatment of the design optimization. For a single stakeholder these weights are also set by this one stakeholder. In addition to this single stakeholder need translation complexity, the previous section identified the existence of multiple coupled stakeholder needs. This further complicates the formulation of an objective function, i.e. value, the constraints and ultimately the selection of the “optimal” design space. The origin of the multitude of multiple stakeholders from the life cycle considerations is discussed in the first paragraph. These stakeholders are likely to have conflicting needs, which need to be combined in a single value measure for comparison. This is discussed in the second paragraph.

Dependency on the life cycle Function and resulting performance of the design are considered over the life of the system, i.e. the life cycle. As a consequence, *value* is also determined by the complete life cycle of the product. Each design ideally starts with an identified need (or opportunity) as shown in Figure 2.10. The life cycle of the product resulting from this need, consists of multiple phases: product, manufacturing and support[23]. These and the design’s influence onto the various phases are shown in Figure 2.10. That is, the conceptual design phase, which is the focus in this thesis, has to incorporate and (ideally) address issues of all other life cycle phases, not only the “product use” phase. This is illustrated by the arrows in Figure 2.10. The consequence of this dependency is that decisions made in the conceptual and preliminary design determine 80% of the performance of the system in the other product life-cycle phases[23, 111]. The linear time progress illustrated in Figure 2.10 requires a more iterative nature, e.g. information obtained in the detail design phase can affect decisions made in the conceptual design phase. This “design process agility” can be provided by the available computing power in combination with multidisciplinary design optimization as will be discussed in Section 2.4. Not all life cycle phases are fully controlled by the (aircraft) manufacturer, as indicated by the non grey

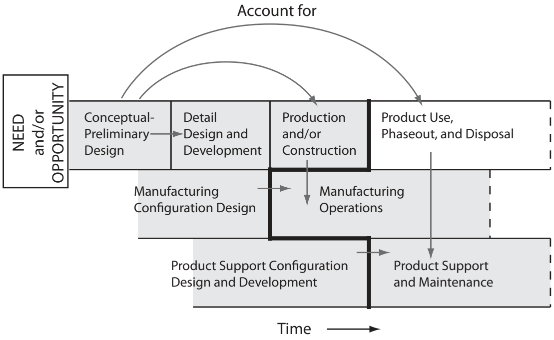


Figure 2.10: Product, manufacturing and support life cycles, adapted from Blanchard and Fabrycky[23], and their relation (represented by the arrows) to other phases and life cycles.

area. This introduces additional difficulties into the conceptual design. The heavy vertical line denotes the separation between the acquisition and the utilization phase. Cross life-cycle influences also exist, the choices made during the manufacturing operations influence the production and construction phase. As an example, the choice for a certain manufacturing process might adversely affect the environmental impact. Finally the product support and maintenance, is intended to influence the life time — either economical life time (ELT) or part/product life time (PLT) — of the product which has a direct influence on the environmental impact. The life cycle dependency of value introduces a multitude of needs from various stakeholders onto the design. Consider, that functions and costs are stakeholder specific properties: acquisition of an aircraft introduces acquisition costs for the airline, which are revenue from the point of view of the manufacturer. This results in multiple potentially conflicting requirements which are to be represented in a single *value*. For the manufacturer these conflicting requirements have to be solved by finding the appropriate balance between the performance of the design and process, represented in the weight factors. Nevertheless this formulation is subjective in that it is based on expected stakeholder behaviour.

2.3.2 Incorporating environmental impact

Product value is difficult to predict without considering environmental impact. Incorporating environmental impact considerations requires addressing the system-of-systems complexities introduced in Section 2.1 (evaluative, behavioural and structural). To reduce the product environmental impact, the value engineer should balance the *necessary* functions and the environmental costs, both of which are dependent on system-of-systems considerations, in an appropriate value measure on which the technologies are to be evaluated or an appropriate formulation of the MDO problem.

Furthermore, if VE is to support design for sustainability it should address and overcome the implicit assumptions as identified by Green[66]; 1) The function of the component being studied is an objective characteristic which remains constant over time. The problem can be identified and is well structured, although real world problems are fuzzy, dynamic and ill defined. 2) Each alternative design solution is engineered to provide an equivalent level of performance, allowing an assessment on the basis of cost alone. The first assumption is invalidated by the dependency of the environmental impact measure on the stakeholder behaviour which changes constantly. The second assumption is not met since novel technologies, required to achieve the environmental impact reduction, induce new previously not portrayed behaviour.

The current incorporation of environmental impact, i.e. the formulation of the MDO formulation is discussed in the first paragraph. The second paragraph illustrates the inadequacy of this approach if stakeholder behaviour is incorporated.

Current environmental impact treatment In the design of aircraft the externalities/ environmental impacts are often considered as limits or constraints to the design space[149, 182]. As a consequence, the externalities are only addressed as limits to the performance, or intended function of the product. From a aircraft development programme perspective, over-achievement of these constraints — decreasing the design's environmental cost without increasing value — is therefore considered to be an undesirable resource shift from the goal of affordability and performance. As identified in the previous section, this budget control is too limited if environmental impact reduction is to be achieved and sustainable products are envisioned.

Two combinations of environmental cost decrease and performance are identified;

1) environmental cost decrease is in line with performance increase, and
2) environmental cost decrease adversely affects performance.

Examples of the first category are carbon dioxide emissions, which are proportional to fuel consumption and material use which is proportional to weight and cost. Improvements in this category are naturally considered during design as they increase the desirability of the product for the customer. Examples of the latter category are NO_x and CO emissions and noise, which are limiting the operation of the aircraft and are consequently treated as constraints. Reductions in this category need external pressure or incentives to be considered in design.

Coupled nature of environmental impact and solution The extended QFD framework identified the coupled nature of the needs and wants of the stakeholders. These *true* needs and wants of *all* stakeholders of the design are to be translated in functional requirements, performance requirements and constraints[110]. This translation from qualitative needs and wants to quantitative requirements is far from trivial. This is further complicated by the coupling of stakeholder needs and technical solution. That is, the environmental impact goals are set by the current behaviour — *ceteris paribus* — whereas the newly developed system induces alternate behaviour, impacting the environmental impact resulting in changed system requirements. Consider as an example the carbon dioxide emission goal I_g, assuming that I is the result of technology use U and per use impact T,

$$I = UT, \tag{2.5}$$

assume $I_0 = 1.25 I_g$, consequently the technology reduction goal is set to $T_n = 0.8 T_0$. This novel technology, however also affects the use, assume an increase of $U_n = 1.1 U_0$.

This results in an impact which is still 10% above the intended goal. These numbers are chose arbitrarily, for the actual proposed solutions these couplings are yet to be investigated. Nevertheless, it is assumed that appropriate requirements can be set for the technologies and that they can be translated into quantitative objectives and goals.

Environmental value The current treatment of environmental impact only addresses the system-of-systems part of environmental impact indirectly; by increasingly strict regulations. The small reversibility of novel aircraft, i.e. undoing or correcting for their impact is difficult and prone to time lag, mandates a preemptive incorporation of environmental impact in the conceptual design phase.

In addition to this, legislation is limited to known environmental costs and performance measures. This leaves the category of — yet — unknown environmental impacts unaddressed. To include and evaluate these in the design, an active search for the actual environmental costs of each product is required. Since the list of environmental costs is incomplete and subject to change, design requirement updates, required to reduce — newly discovered — environmental costs are likely to occur. The resulting value engineering approach, applied to environmental impact, is therefore considered to be a method of finding the appropriate balance between the benefits — experienced by few — and the costs — experienced by (future) many. Both the value and the environmental cost require a more thorough understanding and additional capability tools, not present in the systems engineering toolbox to analyze the product impact during its life-time. Especially since many uncertainties still exist in determining the set of environmental cost parameters of a novel design, the coupling of stakeholders and the resulting emerging behaviour.

2.3.3 Concluding remarks

VE is used as a means to translate the quantitative needs and wants for a given solution space into a MDO formulation. It is considered an iterative approach since the chosen value is dependent on the stakeholders and their needs, which are a function of the new designs opportunities. These opportunities only become clear after the completion of the design and its introduction in the aviation system of systems. MDO only addresses a single solution domain, VE compares various solution domains and their "best solutions" on the basis of of a inter-solution quantity: value. This value is mathematically defined as the ratio between the product benefits, defined by the stakeholders, and the costs. Due to the proposed stakeholder approach for addressing environmental impact, the benefits are a function of the multitude of stakeholders present in the product life-cycle. The combination of these stakeholder needs into a single value is subjective. Furthermore, if costs are interpreted as environmental costs, these become dependent on system-of-system level considerations, i.e. stakeholder behaviour, as well.

2.4 Multidisciplinary Design Optimization

Section 2.3 addressed the formulation of the mathematical problem from the stakeholder needs, proposed solution domain and environmental impact. It is assumed that this has been done properly and that solving the (restated) MDO formulation will provide the best solution within the chosen solution domain,

$$\begin{aligned} \min_{\boldsymbol{x}_D} \quad & \phi(\boldsymbol{x}_D, \boldsymbol{x}_E(\boldsymbol{x}_D)) \\ s.t. \quad & \\ & \boldsymbol{g}(\boldsymbol{x}_D, \boldsymbol{x}_E(\boldsymbol{x}_D)) \leq 0 \\ & \boldsymbol{x}_{D,lb} \leq \boldsymbol{x}_D \leq \boldsymbol{x}_{D,ub}, \end{aligned} \tag{2.6}$$

where $\boldsymbol{x}_D$ are the design variables and $\boldsymbol{x}_E(\boldsymbol{x}_D)$ the environment variables which are influenced by the design. Directly solving Equation 2.6 is impossible for complicated engineering systems as the mapping of $\boldsymbol{x}_D$ and $\boldsymbol{x}_E(\boldsymbol{x}_D)$ onto ϕ and g is unavailable. As a consequence, simply selecting the appropriate $\boldsymbol{x}_D$ which satisfies $g < 0$ and minimizes ϕ is impossible. To address this behavioural complexity, the task is subdivided in multiple smaller tasks, i.e. decomposition. Consequently, structural complexity is introduced to address the behavioural complexity.

These multiple tasks are still related to the same system, and consequently they are coupled, i.e. dependent on each other. For the technical solutions proposed to address the environmental impact of aviation — e.g. blended wing body (BWB)[104, 183] and Prandtl plane (PP)[64, 146, 147, 183] — this coupling is even more pronounced due to the presence of multi-functional elements. Consider the centre body of the BWB, this houses the passengers, provides lift, stability and controllability and supports the engines. Changes in the design to improve a single function, e.g. drag reduction, directly affect the performance on the other functions, e.g. payload capability. Obtaining an optimal balance, i.e. *synergy*, between the various functions is essential for a successful design. This requires treatment of multiple disciplines in each optimization instead of a single discipline optimization, complicating the design. Furthermore, the single function performance change due to a design adaptation cannot be inferred from experience. That is, only limited experience with these novel technologies has been acquired, introducing uncertainty in the correlations and uncertainty in the behaviour of the complete system.

To be able to address the structural complexity the increasing computational resources are employed. This requires the translation of the real system optimization into the computational domain. In practice this means that the actual system behaviour — subdivided into several tasks — is emulated by a set of computational models. The replacement of the real system by a (limited) set of mathematical and computational models introduces limitations in the evaluation of the system behaviour.

The imperfections introduced by this translation result in a difference between the actual design space and *model design space*, shown schematically in Figure 2.11. The real world design space, or set of systems and their resulting behaviour, is depicted on the left. Each point or design is represented by a mathematical or computational model in the computational domain. The set of computational models within the mathematical constraints is considered the model design space, depicted on the right. The complexities arising from emulating the real system in a mathematical or computational domain are dubbed *modelling* complexity.

In summary, the real world problem is managed by a translation into the computational domain to solve the complex design problem. For the first section it is assumed that this translation is perfect. The solution the computational problem as given by the objec-

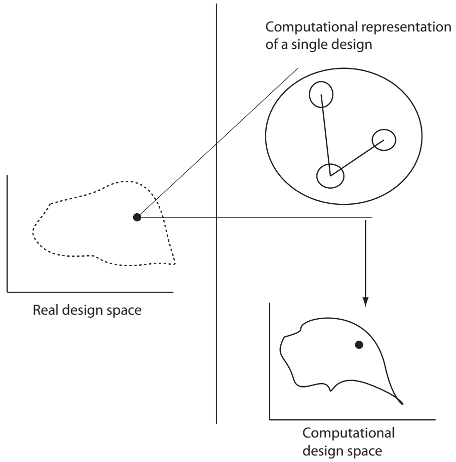


Figure 2.11: Design representation in the computational domain and consequent difference in design space.

tive, constraints and bounds is still difficult to analyze and optimize. The employed MDO methods are considered in the following section. The errors resulting from the translation from real world to computational domain are treated in subsequent section.

2.4.1 Structure, coordination and optimization

To be able to determine system behaviour, complicated engineering systems are decomposed into smaller aspect and/or subsystems[184, 190]. The subsystems can again be interpreted as systems and further divided until a set of manageable tasks is obtained. These tasks are distributed over multiple people and computers shortening the design lead time.

These subsystems are part of the original system and are dependent on each other, i.e. the output from a task is required as input in another task. Artificially breaking these dependencies allows for the concurrent treatment of these tasks, but simultaneously introduces the need for external coordination. Consequently, this decomposition introduces *structural complexity* [177] in the design procedure to address the *behavioural complexity*. Structural complexity is assumed to be measurable by the number of elements in the process (process complexity) or product (product complexity) and their interconnections [122, 150]. First, ways to decompose the system are discussed. Second, the incorporation of coordination between the dependent tasks is substantiated.

Decomposition

Generally decomposition can 1) divide the system of interest in smaller elements, i.e. subsystems, 2) view the system from various disciplines, i.e. aspect systems, or 3) a combination of both. Figure 2.12 depicts a general case of decomposition, in which the hypothetical

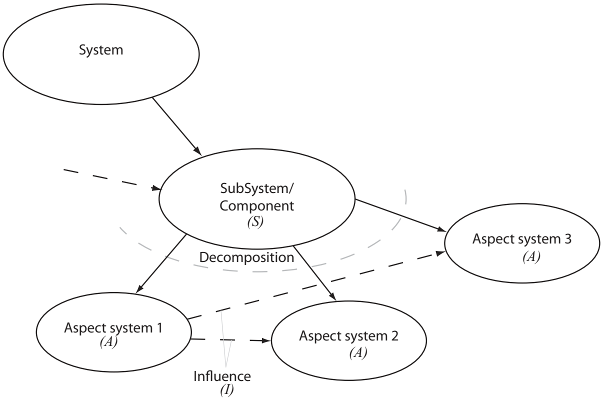


Figure 2.12: System decomposition into aspect systems and interactions.

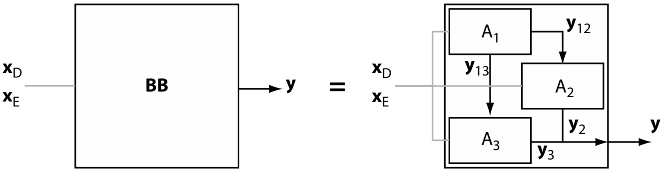


Figure 2.13: Model input and output and decomposition into three coupled aspect systems describing a design.

system is decomposed into its subsystems or components S and their couplings, which are then further decomposed into aspect systems A_i and their dependencies I. The level — system, subsystem, component — at which decomposition into aspect systems is performed is determined by the analysis capability available to the designer. In this process of decomposition it is assumed that the total system S can be represented by a finite set of known aspect/subsystems A_i and dependencies I,

$$\bigcup_i A_i \cup I = S. \tag{2.7}$$

A single aspect system i is treated as a black box which's behaviour can be described by a function f,

$$\boldsymbol{y}_i = f(\boldsymbol{x}_D, \boldsymbol{x}_E, \boldsymbol{y}_{j,i}), j \neq i, \tag{2.8}$$

which is dependent on the original design and environment vector $\boldsymbol{x}_D, \boldsymbol{x}_E$ and the output of other disciplines $\boldsymbol{y}_{j,i}$. Assume that subsystem S is system decomposed into three aspect systems as shown in 2.13. The coupling requires that in order to evaluate black box i the values of the dependent variables $\boldsymbol{y}_{j,i}$ are known from the other black boxes.

To decompose the set of aspect systems even further and allow concurrent evaluation of the aspect systems, the dependencies are artificially broken. In practice this means that "reasonable" values are assumed for the dependent variables. This introduction of surrogate variables $\boldsymbol{y}^*_{j,i}$ is shown in Figure 2.14. These additional artificial independent variables allow the system to be considered in black box 1 to be different from the one considered

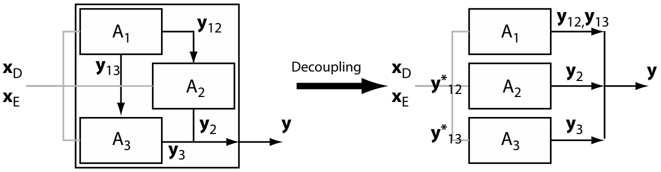


Figure 2.14: Decoupling of the subsystems and the resulting surrogate variables.

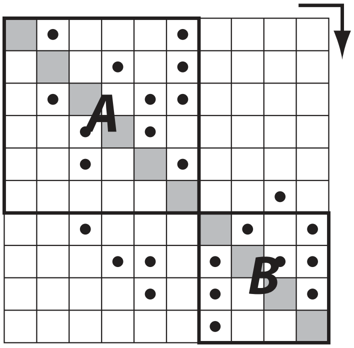


Figure 2.15: Design structure matrix.

in black box 2. Mathematically, $y^*_{j,i}$ is generally not equal to the actual $y_{j,i}$, i.e. the system is inconsistent. As a consequence, decoupling introduces the need for a management of these dependencies, *coordination*. Coordination is consequently the management of the dependencies in order to achieve a consistent design. If each model evaluates the same design — i.e. $y^*_{j,i} = y_{j,i}$ —, the design evaluation is considered *consistent*. Furthermore if such a consistent design satisfies all constraints, it is denoted *feasible*.

Design Structure Matrix A tool commonly used to visualize the dependencies between aspect/subsystems, is the design structure matrix (DSM), shown in Figure 2.15. The diagonal shows the aspect systems representing the complete system and the off-diagonal terms show the existence and direction of a dependency. Tightly coupled aspect systems should be treated simultaneously as aggregates, whereas uncoupled systems can be treated independently. A somewhat arbitrary grouping into two aspect system aggregates is shown in Figure 2.15. If the diagonal from upper left to lower right is interpreted as the order of treatment of the aspect/subsystems, the information in the DSM allows for the reorganization of treatment in order to minimize analysis time. To minimize re-evaluating aspect systems, the number of backward dependencies should be minimized. In this DSM it means having as little elements in the lower left triangle as possible, to generate the most efficient treatment of all subsystems. In the example it would therefore be more efficient to consider aggregate B before A. Systematic permutation of rows and columns can be used to achieve more efficient structures. Algorithms to do this automatically do exist as illustrated by for instance Browning[26].

Incomplete representation Up to this point no mention has been made of which disciplinary views should be considered or which aspect systems are to be treated in the design process. The first example considered three aspect systems and the DSM incorporated 2 aspect systems and ten disciplinary views. These are chosen arbitrary, this is not the case for an actual design. From the large amount of possible aspect systems, the analysis is often restricted to aspect/ subsystems which are considered to dominate the system behaviour on the objective ϕ and constraints g, to limit the computational burden in the conceptual design. Identification of the dominant aspect/subsystems is difficult for existing systems, e.g. aircraft, despite the fact that both the required aspect systems, their interactions and their relative importance are known from previous designs. For novel technologies and systems this identification is even more the difficult, since either aspect systems, interactions, their relative importance or a combination thereof are not known to the designer beforehand.

This imperfect translation results in a different representation of the behaviour of the design. Since the optimizer tends to exploit the inadequacies in the models, the model design space is further restricted by *model induced constraints* which account for the inadequacies of the model design space representing real world behaviour.

Coordination and optimization

The need for coordination, or the management of dependencies between aspect/subsystems, has been identified to steer the subtasks towards a consistent design and the achievement of the system goal. In particular in concurrent engineering, where tasks are performed simultaneously to decrease lead time, tearing or decoupling of dependencies is common. Mathematically coordination ensures that surrogate variables are equal to the actual dependent variables for the final design,

$$\boldsymbol{y}^*_{j,i} = \boldsymbol{y}_{j,i} \tag{2.9}$$

Various MDO methods treat this coordinating task in different ways and at different (system) levels.

Optimization of complicated engineering systems, particularly when part of a complex system-of-systems, is a multidisciplinary exercise. That is multiple disciplines need to be considered including their dependencies in order to optimize the system. For the highly coupled proposed solutions — BWB and PP — the simultaneous treatment of aspect systems in a single optimization procedure is required to arrive at a feasible solution. However, if coordination and the multidisciplinary optimization can be done appropriately, the benefits from synergy can be significant[104]. Furthermore, if each task is focussed on improving the overall system objective the design process becomes more efficient as well. This in contrast to the individual optimization of each aspect system sequentially, which does not benefit from possible synergies.

Various methods using a single level optimization structure have been developed and can be grouped into three categories 1) All at Once (AAO), 2) Single discipline feasible (SDF) and 3) multi-discipline feasible (MDF), where a decreasing responsibility of coordination is attributed to the optimization module[94]. These approaches put all optimization effort on a single optimization procedure, as a consequence the individual tasks are limited to providing data and not at improving the system performance. Besides single level optimization

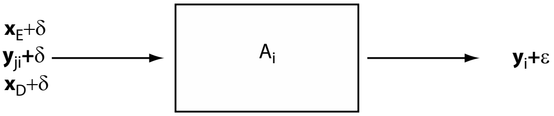


Figure 2.16: Model input and output all subject to their individual error ϵ.

approaches, multi-level approaches have been developed, involving multiple optimizations, both at system and aspect/subsystem level. Examples of multidisciplinary design optimization (MDO) frameworks[94] are, collaborative optimization (CO)[44], concurrent subspace optimization (CSSO) and Bi-level Integrated System Synthesis (BLISS)[171, 172] and its more recent version BLISS 2000[173]. Each method approaches the coordination and optimization in a different way.

2.4.2 Model error uncertainty

As identified in this section, the computational representation of the real world system behaviour is an imperfect one. When the effect of this imperfection, i.e. the error, is not known from comparisons with measurements, uncertainty about the validity of the model results is introduced. A schematic representation of the errors, δ, ϵ is shown in Figure 2.16. The output error ϵ is of particular interest in this section. First a more formal treatment of the sources of model error is given, after which a criterion is devised for the evaluation of the model useability.

Sources for model error

In general the design is represented in the computational domain by a set of parameters. Given a model A_i from I possible models, this set of parameters is subdivided into model input and output parameters. This set of parameters consists dependent, independent and environmental parameters. This distinction is made to illustrate the limited influence of the designer on the dependent parameters. Consequently, this set of parameters is a limited set of the infinite set describing the real system. That is, the computational domain is restricted to the features considered in model A_i. Capturing the infinite set of parameters in vector $\boldsymbol{\xi}$ results in

$$\boldsymbol{\xi}_m \subset \boldsymbol{\xi}, \boldsymbol{\xi}_m = [\boldsymbol{x}_D, \boldsymbol{x}_E, \boldsymbol{y}] \tag{2.10}$$

From this set a single parameter is taken to be the parameter of interest r, the real response of the system. If a model i is considered, this parameter of interest should be in the limited set $\boldsymbol{y}$ and is named m_i. Since the value of this variable is dependent on the remaining elements in vector $\boldsymbol{\xi}, \boldsymbol{\xi}_m$ it is written as $r(\boldsymbol{\xi})$ for the real system behaviour and $m(\boldsymbol{\xi}_m)$ for the model prediction. Furthermore, the existence of comparison of measurement data and model predictions — r and m_i — for a given set $\boldsymbol{\xi}$ and $\boldsymbol{\xi}_m$ is denoted $\boldsymbol{\xi}_v$. The — possible — difference in real behaviour and model prediction is the error,

$$r(\boldsymbol{\xi}) - m(\boldsymbol{\xi}_m) = \epsilon(\boldsymbol{\xi}, \boldsymbol{\xi}_m), \tag{2.11}$$

where the model index i is omitted for brevity. Mahadevan[106] identified various sources of this error, all requiring probabilistic treatment [52]. Rewriting above equation with the specific sources of error identified by Mahadevan[106]

$$r_{obs}(\boldsymbol{\xi}) + \epsilon_{exp}(\boldsymbol{\xi}) \equiv m(\boldsymbol{\xi}_m) + \epsilon_m(\boldsymbol{\xi}, \boldsymbol{\xi}_m) + \epsilon_n(\boldsymbol{\xi}_m), \tag{2.12}$$

which states that the actual response, r_{obs}, can be approximated by model response, $m(\boldsymbol{\xi}_m)$, but is different from it, due to three possible sources of error. The actual response $r_{obs}(\boldsymbol{\xi})$ cannot be observed perfectly and is subject to experimental error ϵ_{exp} [106, 114]. Furthermore, it is important to note that, although the actual response can be approximated by a model, no causal relationship exists between model response and real response. Furthermore, the model response is subject to 1) model form error, determined by the assumptions on which the model is based, $\epsilon_m(\boldsymbol{\xi}, \boldsymbol{\xi}_m)$, and 2) numerical error, due to the discrete implementation of the problem, $\epsilon_n(\boldsymbol{\xi}_m)$.

The experimental error, ϵ_{exp} can only be quantified by performing (multiple) experiments, the numerical error ϵ_n is completely determined by the numerical approach and the model form error ϵ_m requires comparison of model predictions and actual response comparisons [106, 114]. Note that the error in model input is implicitly included in the difference between $\boldsymbol{\xi}$ and $\boldsymbol{\xi}_{\boldsymbol{m}}$.

All three errors are generally not known with certainty. The experimental error in general induces a probability distribution due to variations in conditions, inaccuracies in measurement equipment and difficulties in isolating the parameter of interest[114]. More often a direct comparison between measurements and model prediction for $\boldsymbol{\xi}$ and $\boldsymbol{\xi}_m$ is not available. This absence of overlap in the domains of model application and validation, introduces additional uncertainty in the model error [52, 136]. These uncertainties affect the belief in the validity of the model in the domain of interest. A framework to reduce avoidable uncertainties by including all information available to the designer might aid in the allocation of resources intended for improving belief in model results.

Uncertainty in the model predictions is subject to various sources based on the sources identified by Kennedy[92] and Beyer[21];

1) uncertainty in model input $\boldsymbol{x}_D, \boldsymbol{y}_{j,i}$ due to uncertainty in couplings, either existence and value.
2) inherent variations in design properties, e.g. tolerances
3) Inherent uncertainty in environmental input $\boldsymbol{x}_E$
4) uncertainty in the correct prediction of $\boldsymbol{y}_i$ by the model

In particular the fourth uncertainty, related to the model validity is considered here due to the reliance on model predictions in the design of novel technologies.

Model agreement

Nature is considered to behave consistently, as has been found during numerous experiments. Consistent[5] is hereby defined as behaving in a similar way given the same conditions, i.e. an experiment is repeatable. For this paper mathematical models are considered, since they allow for inferring behaviour in non-validated states. Furthermore, in order

---

[5] Note that in this section consistent has a different meaning than identified in the MDO section.

to be acceptable the predicted behaviour should be *in agreement with* the real behaviour in the domain of interest. *In agreement with* is defined here as being in agreement with each other. One can therefore conclude that;

> *Given that two models are not in agreement with each other in a region, it must be concluded that at least one of them must be incorrect.*

This statement cannot be used to determine which model correctly predicts real system behaviour, but at least gives an indication to whether a combination of models is deemed acceptable in a domain where no information about the real system behaviour is available. For two models four combinations exist; 1) both models are consistent with each other and real behaviour 2) both models are consistent with each other but not with real behaviour 3) the models are inconsistent with each other and one is inconsistent with the real behaviour 4) the models are inconsistent with each other and both are inconsistent with the real behaviour. Mathematically this results in attributing a probability of $\mathcal{P} = 0.5$ on model validity when either model agreement or disagreement is observed, which is interpreted as ignorance. As a consequence, a comparison with real behaviour is inevitable to arrive at a definite conclusion[6].

The purpose of the model, translated into a range of acceptable error, should be included in the consistency evaluation. Assuming that each element in the set of parameters of interest can be treated individually having its own range of acceptable error, a single value $m(\boldsymbol{\xi}_m)$ is considered here. Alternative methods of comparison exist [135, pp. 43], however for a single parameter comparison the relation for consistency can be written as,

$$m_1(\boldsymbol{\xi}_{m_1}) - m_2(\boldsymbol{\xi}_{m_2}) \in [\epsilon_*, \epsilon^*] \tag{2.13}$$

where $m_i(\boldsymbol{\xi}_{m_i})$ is the parameter of interest predicted by model i for state $\boldsymbol{\xi}_{m_i}$ and $[\epsilon_*, \epsilon^*]$ is the acceptable error range set by the designer. $\boldsymbol{\xi}_{m_i}$ is a finite vector of parameters describing the situation $\boldsymbol{\xi}$ under consideration as required by model i. As a result, $\boldsymbol{\xi}_{m_i}$ should be equivalent for both models, i.e. describe the same condition. Finally, if one of the models is replaced by the real behaviour $r(\boldsymbol{\xi})$ a relation for the model agreement with real behaviour is obtained, i.e. validation[7].

In conclusion, agreement between model predictions is not a check for model validity, but can be used as an indicator that further investigation is required. The acceptance of the behaviour predicted by a model or combination of models is considered dependent on the preference and knowledge of the designer, due to the influence of the designer on 1) the selection of the model(s) and 2) the error which is considered acceptable.

Model form error

The previous section showed the inability to arrive at a conclusion about model validity without measurement data for the design vector of interest $\boldsymbol{\xi}$. Additional information might be available for an alternative $\boldsymbol{\xi}_v$. As a consequence, a method is proposed to infer the model form error from a state where observation data are available to the state of interest,

$$\epsilon_m(\boldsymbol{\xi}, \boldsymbol{\xi}_m) = \epsilon_m(\boldsymbol{\xi}_v, \boldsymbol{\xi}_{m_v}) + \Delta\epsilon_m(\boldsymbol{\xi_v}, \boldsymbol{\xi}, \boldsymbol{\xi}_m, \boldsymbol{\xi}_{m_v}) \tag{2.14}$$

---

[6] This is not completely true as indicated in “How experiments end” by P. Galison [60].

[7] Correlation does not mean proof of the model. Affirming the consequent; If p then q, observe q, then p is true, is incorrect since p might not be the only explanation of q being observed.

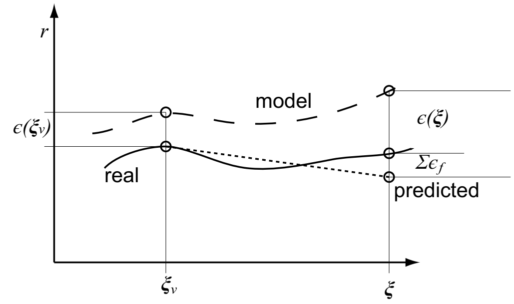


Figure 2.17: Predicted and actual error due to a difference in state.

In states inside the region where observations are available (interpolation) this relation is considered less difficult than for extrapolation. Especially outside the bounds of conventional technologies this treatment is more difficult [52, 135]. Henceforth, the focus will be on the extrapolation error, assuming a similar treatment can be devised for the interpolation error. This is shown schematically in Figure 2.17. Note that this requires a probabilistic treatment as certainty without measurements is impossible. The appropriate framework will be discussed in Chapter 3.

Numerical model error

Some special considerations have to be given to numerical models — e.g. finite volume, finite difference and finite element models. These models are based on differential properties, numerically integrating them to obtain the solution in the complete domain of interest [114, 151]. This assumes that — if implemented correctly — the summation of these relations provides realistic results. In this case special care has to be taken with the implementation of the problem, i.e. an additional layer is added, numerical implementation of the analytical model, besides the analytical solution comparison to real behaviour [106]. This has been depicted in Figure 2.18, and introduces the additional error ϵ_n. This error is considered to consist of several parts, 1) grid dependence, ϵ_g, 2) convergence , ϵ_c, and 3) implementation of boundary and initial conditions , ϵ_{init}. As a first estimate of the error,

$$\epsilon_n = \epsilon_g + \epsilon_c + \epsilon_{init} \tag{2.15}$$

In aerodynamics, Richardson extrapolation may be used to estimate [152] the effect of grid size. For the convergence error, convergence of the continuity properties (momentum, mass and energy) and the variable of interest, e.g. lift, is usually employed. Finally the dependence on the implementation of boundary conditions and initial conditions should be investigated. This could also be classified as model error ϵ_m. One consequence would be that putting a lot of effort — i.e. resources — in achieving a very small numerical error might be negated by a large implementation error. With respect to resource management this would mean that equal emphasis should be put on solving the right problem (ϵ_m) and solving it correctly (ϵ_n).

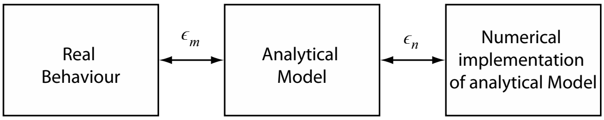


Figure 2.18: Additional layer of consideration, due to the method of solving the equations.

2.4.3 Considerations

Despite the simplifications incorporated to arrive at a mathematical formulation from the fuzzy design problem in QFD, the optimal solution is not easily identified. Two important aspects of this multidisciplinary treatment have been considered; 1) the structure and treatment of the multidisciplinary analysis and optimization consisting of multiple models and 2) the inherent error present in the models emulating the single (aspect) system behaviour. The MDO framework addresses the behavioural and structural complexity, but is hampered by modelling complexity. This modelling complexity is considered by focussing on the sources for errors in model predictions. This modelling complexity requires a probabilistic treatment. In particular effort is put into estimating the model form error.

2.5 Concluding remarks

This chapter discussed several problems occurring in the treatment of environmental impact reduction of complex adaptive systems. Four complexities have been defined and have been discussed in order to identify their characteristics when they are treated. The identified complexities which will be treated in this thesis are

- evaluative complexity
- behavioural complexity
- structural complexity
- modelling complexity.

Furthermore, the problem is subdivided into a system-of-systems level and system level treatment. Although the definition of where a system stops and the system-of-systems starts is subjective: a definition which is considered workable is formulated. A system is a collection of elements where the behaviour of all of these elements can be controlled by a single entity. This in contrast to the system-of-systems, where such a central control element is lacking. This lack of central control makes steering such a system-of-systems towards, for instance, less environmental impact a non-trivial task.

System-of-systems The system-of-systems is composed of stakeholders, which have an opinion on what should be the goal of a system, e.g. aircraft, resulting in evaluative complexity. The sheer number of stakeholders present in aviation results in structural complexity. Furthermore, the goal of environmental impact reduction is hampered by a lack of understanding of all interactions between these stakeholders, resulting in behavioural complexity. At the system of systems level these three complexities are investigated using quality function deployment. In focussing on the system development, the conflicting stakeholder requirements resulted in coupled stakeholder needs and wants from the system. A stakeholder has been defined as an individual or organization who can affect the development of the novel technology. This includes the externalities of the technology which are considered to become empowered by the government.

System At the system level, the difficult translation from qualitative needs into a mathematical formulation treatable by a computational MDO framework is discussed using value engineering. Furthermore, the structural complexity tackled by decomposition and coordination as well as behavioural complexity. This translation from the real world system into the computational domain resulted in an imperfect and limited system description in the model design space. In particular for novel technologies, where the validity of models is unknown this results in unknown errors produced by these models defining the model design space. The sources of these errors have been discussed as modelling complexity.

The way forward These considerations and definitions are used in the remainder of this thesis. In order to treat the complexities in sufficient detail, three elements of the previously identified complexities in “design for sustainability” are separately considered by appropriate tools,

1) The complexities at the system-of-systems level. In particular the modelling of stakeholders in a computational domain and the coupling of behaviour, technology and the resulting environmental impact.
2) The structural and behavioural complexity present in the conceptual design of a system, using a multidisciplinary design optimization framework.
3) The modelling complexity and in particular the uncertainty in model errors occurring for (novel) technologies.

To capture the broad range of technologies proposed, all with their difficulties, the tools are applied to different technologies. An integrated approach simultaneously addressing all three challenges by a single tool is not considered feasible. As a consequence the integration requires human intervention.

Chapter 3. Research methodology

"All models are wrong, some are useful."
George E.P. Box.

The previous chapter addressed three extensions to the QFD framework: 1) the evaluation of environmental impact at the system-of-systems level and 2) the concurrent treatment of disciplines in the increasingly coupled solutions at the system level, 3) the increasingly computational treatment of design results in inherent sources of model-reality discrepancies. Although various methods exist to implement these extensions a choice has been made for the implementation which is considered most suited for the problem at hand. Schematically the proposed methods are shown in Figure 3.1 and their relation to each other is depicted in Figure 3.2. As discussed in Section 2.2 the interactions between the stakeholders is of particular interest for environmental impact. To predict the effect of this interaction a simulation environment is used, i.e. the Agent Based Modelling and Simulation (ABMS) approach. This approach has been shown to allow modelling of CLIOS and allows for a bottom up approach, focussing on the modelling of the stakeholders and their interactions[130]. The ABMS approach thus couples the behaviour of stakeholders and

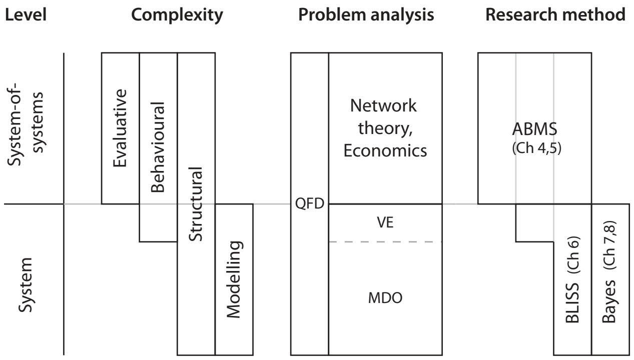


Figure 3.1: Schematic overview of system level, complexity and available and proposed tools addressed in this thesis.

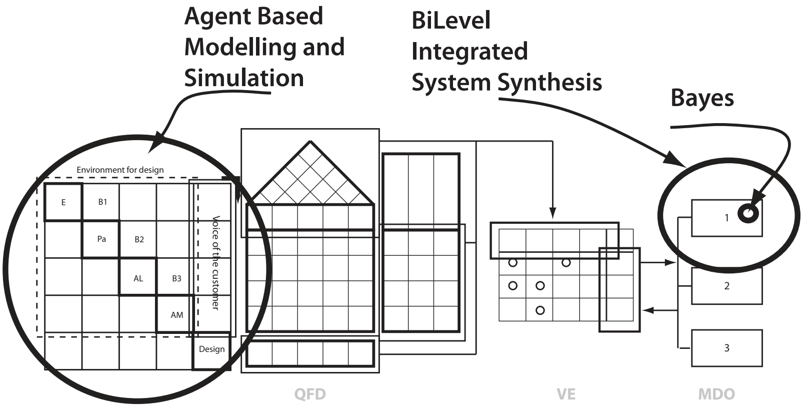


Figure 3.2: Implementation of the QFD/VE/MDO framework, Agent Based Modelling and Simulation (ABMS), Bi-Level Integrated Systems Synthesis (BLISS) and probabilistic analysis (Bayes).

allows for the prediction of whether stakeholders needs are met by a design accounting for the intertwined environment the product has to operate in. The product however needs to be sufficiently mature to allow for this ABMS evaluation. As discussed in Section 2.3 and Section 2.4, the design of the product in response to the needs is addressed by VE and MDO. The trend of increasing complexity of the aircraft system results in the subdivision of the work and distribution over multiple (sub)contractors. This decomposition of the aircraft requires a different approach in coordination. Ideally one would want each of these subcontractors to work towards the overall increase of the objective function. This is facilitated by the Bi-Level Integrated System Synthesis (BLISS) approach. MDO is a computational approach, using models to emulate the real system. All optimization operations are performed on these models. The inherent differences between the model prediction and real world system behaviour are a source for uncertainty. This is treated using a probabilistic framework based on Bayes' update rule.

The modular approach adopted by ABMS make it a suitable modelling environment for the continuously changing composition of aviation. The background of this framework is discussed in Section 3.1. The strategy chosen by the BLISS framework to facilitate the MDO approach is discussed in Section 3.2. Finally, one particular source of error, model form error, and a means of estimating its magnitude is addressed in Section 3.3.

3.1 Agent based modelling and simulation

As defined in the previous chapter, the emerging behaviour of aviation is defined by the behaviour and interactions of the multitude of stakeholders. To investigate these interactions in more detail and acquire a better understanding of their effect on the environmental impact of a novel technology a computational framework is created using Agent Based Modelling and Simulation paradigm (ABMS). ABMS has its historical roots in the study of complex adaptive systems (CAS), and is therefore considered suitable to tackle the evaluative, behavioural and evaluative complexity encountered in the environmental impact evaluation of aviation. In particular the changing structure of CAS can be addressed by the ABMS paradigm. This in contrast to inflexible macro-economic principles. To address complexities at the system-of-systems level, ABMS uses techniques from discrete event simulation and object-oriented programming. The foundations of this paradigm and its benefits to the understanding of the coupling of behaviour and technology impact at the system-of-systems level are detailed first.

The implementation of the emerging behaviour of the complex adaptive system of aviation is a non-trivial task. Discrete event simulation provides a mechanism for coordinating the interactions of individual components, in this case agents/stakeholders and environment. The object oriented programming paradigm accommodates a structure to classify and implement agents in a software environment.

3.1.1 ABMS paradigm

The Agent Based Modelling and Simulation paradigm is used to use the advantages of modern computing resources to emulate the behaviour and interactions of the aviation stakeholders and the resulting environmental impact. In particular the coupling between the stakeholder behaviour and the technology, and the impact of this coupling on the environmental impact of aviation. This requires the emulation of the behaviour of various stakeholders in a software simulation environment. These stakeholders are implemented in independent decision making entities, i.e. *agents*[129, 128]. These independent decision making stakeholder furthermore require an environment in which they can interact. The two foundations of ABMS are discussed for the creation of a ABMS;

1) the environment in which stakeholder interactions are regulated is based on discrete event simulation, and
2) the implementation of the stakeholders is based on the object oriented programming paradigm.

Finally, the steps to be taken to create a ABMS environment are shortly discussed.

Agents

Agents are elements in the simulation which react to and affect the environment according to their internal decision rules. Agents are created from independent decision-making components in CAS[134], in the case of aviation; the stakeholders. Airlines, airports, passenger groups, people living near the airport can be represented by an agent in a simulation environment. Alternative interpretations of agents as elements influencing the environment, which would include technology, as an agent do exist, however the focus lies on the interaction of stakeholders and their impact on the environment in the context of aviation. As a consequence, each stakeholder is an agent and, in line with Bandura[9], each agent consist of attributes and behavioural characteristics. Attributes define what a given agent is within a class, e.g. scheduled airline, charter airline or low cost airline, and behavioural characteristics define what an agent does, e.g. buy an aircraft, set frequencies or improve service. This corresponds to the previously identified characteristics P, and B, which are influenced by the environment E. This influence of the environment is limited to the change in agent attribute values, e.g. profit, number of products bought and passengers transported.

The decision making of agents is considered to be driven by an internal model, deciding, based on the attribute values and the environment which behaviour to portray. The general computational steps performed by an agent to emulate behaviour are[134, p 28];

1) Evaluate the current state and establish the current goal,
2) Execute the corresponding actions/ portray behaviour, and
3) Evaluate the results and possibly adapt action for the next step.

In order to reduce the complexity of the agents and allow focussing on the interaction between stakeholders, the additional complexity stemming from the learning capability of agents, i.e. improving or adapting the internal model for decision making, is not considered. Agents consequently act according to prescribed internal decision models and "learning" has to be explicitly modelled in the current implementation. The inclusion, albeit external, of this learning is important in the considerations of novel technologies as these often enable alternative behaviour.

As mentioned, the internal models drive the behaviour of the agents. The sophisticated and often unobservable process of stakeholder decision making, results in the unavoidable introduction of assumptions and simplifications of these internal models. Several items have to be considered in the creation of agent internal models. Despite the availability of all information in the ABMS the availability of this information to agents has to be limited to emulate real world behaviour. Access to information is often limited to the direct interactions between stakeholders and observable items, e.g. total number of sales of products. A further limitation to be considered besides access are memory. Stakeholders have an imperfect memory which affects their decisions, to mimic this in the simulation, agents should be able to store (limited) information from previous decisions. These memory limitations are dependent on the stakeholder, e.g. organizations are considered to have a larger memory than individuals. Finally, the internal models previously mentioned, are a representation of reality, the ABMS itself, if used for strategic purposes, is also part of the decision strategy of the company. This results in self reference, hence simplifications are necessary. In summary, the internal model is subject to four considerations which should be decided upon when creating an agent representation of a stakeholder[134, pp.89]:

1) Sophistication of the stakeholders' decision models,
2) The extent of the information available to the stakeholder and the extent incorporated in making decisions,
3) the amount of information recalled by the stakeholder from previous decisions, i.e. memory, and
4) whether stakeholders have an understanding of (parts of) the complete system.

The remainder of this section will discuss the environment and implementation of the agents and ABMS environment in a computer simulation environment. The next section will discuss the chosen implementation of the internal models to emulate the behaviour of stakeholders.

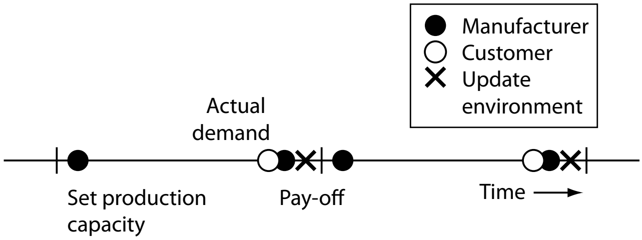


Figure 3.3: Example schedule of events.

Discrete event simulation

In discrete event simulation, the operation of a system or system-of-systems is represented as a chronological sequence of events. Each event occurs at an instant in time and marks a change of state in the system[153]. Consequently, in between events the simulation is considered to be in a constant state. In the current implementation, events are scheduled using an event list, although alternative more sophisticated methods of scheduling exist[153], this prescribed scheduling is considered sufficient as a first indication of the effect of interactions between stakeholders. An example is given in Figure 3.3. The example event, "set production capacity" might be composed of multiple manufacturer agents setting their production capacity simultaneously, iteratively or sequentially based on their predictions of demand and production capacity of other manufacturer agents. This iterative "production capacity setting" can be used to emulate strategic behaviour, i.e. incorporating the opponents behaviour into the decision. "Actual demand" is the event where customer agents choose and acquire the products from the set of available products. This results in a change in the manufacturer stocks, i.e. the third event. Finally the environment needs to be updated, e.g. total number of products sold, orders received and information available to the manufacturers.

Scheduling the updating of the environment determines whether the events are to be considered simultaneously or sequentially. That is the agent bases his decisions on the perceived state of the environment. As a consequence, if the environment is not updated after an event 0, the next event, 1, is based on the same environment as before event 0. As a consequence, the order of the events, $(0, 1), (1, 0)$ has no influence and the decisions can be considered simultaneous. This sequence of events is particularly important in strategic decision making, where the available information — perceived environment — has a direct effect on the behaviour. Consider for example the interaction of airlines which are allowed to test their hypothesis before deciding on the final action as a single event. For a clearer implementation, schedule hierarchy can be created, i.e. multiple events can be grouped in a single event, like the "set production capacity". Consequently, each event might consist of a nested scheduler with an internal (fictional) time.

The considered events in this ABMS implementation include agent-agent, agent-environment interactions and environmental changes. Since agents are limited to stakeholders, a novel technology or product is considered a stakeholder attribute. Furthermore, an example of an environmental change is "replenishment of natural resources", e.g. growing of trees, replenishment of materials in stock, and is not caused by agents *within* the simulation. The software scheduling the events can thus be interpreted as the operating

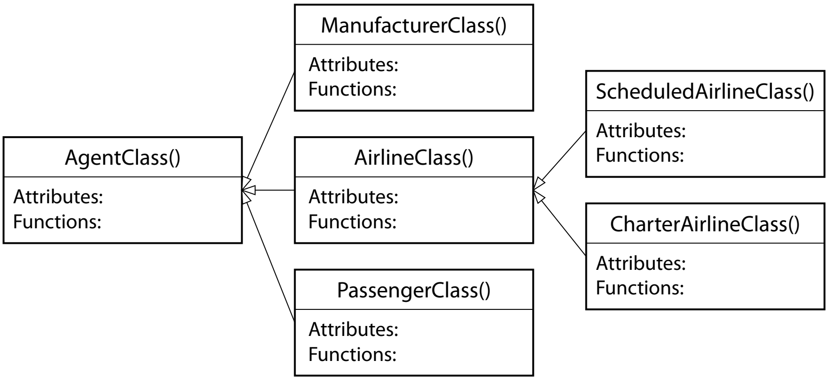


Figure 3.4: Example of a class hierarchy.

environment of the stakeholders. This environment schedules the actions of all agents, keeps track of the overall system data, and regulates the environmental changes, possibly external to the simulation. When the initial conditions, agents and boundary conditions are defined, the time progress remains the only independent variable. This allows for the study of the development of system-of-systems behaviour over time.

Object-oriented programming paradigm

The object-oriented programming paradigm allows for the organization and classification of agents based on their behaviour[134] and for the convenient implementation into a simulation environment, i.e. on a computer. It provides a computational equivalent to the aggregation identified in complex adaptive systems. Object oriented programming uses objects to represent discrete entities, e.g. agents, which are instantiated from classes. A class is considered a template and allows for the easy instantiation of multiple heterogeneous agents. Heterogeneity is here defined as variations in the agent attribute values as classes are based on similarities in behaviour. An example of a hierarchical class structure is shown in Figure 3.4, where the connections denote the inheritance of classes from left to right. This inheritance allows for easy class extension into subclasses, interchange of classes, and creation of multiple heterogeneous objects based on the same class. The latter is especially important since the number of agents employed becomes large rather quickly[62].

This class hierarchy is used to create a database of agent classes, representing stakeholders in aviation. This database is build starting from the general agent class, as a decision making entity, into an airline class, airport class, manufacturer class, passenger class and community class. For the treatment of the environmental impact, this is considered sufficient. Furthermore, the class structure also allows for the instantiation of multiple schedulers which results in a scheduler hierarchy as discussed in the previous section.

Set-up of an ABMS

For the simulation to run, once the appropriate level of aggregation is determined, the interaction properties between the stakeholders need to be determined. The chosen level of aggregation determines the detail which can be captured by the individual agents. Data to be stored at the agent level as well as the system-of-systems level. This results in increasing storage needs with growing numbers of agents. Consequently, the level of detail is balanced by the storage requirements. The more detail captured in diverse agents, the larger the amount of data produced and handled in the ABMS.

To setup an agent-based framework, Kuhn et al.[98] suggest the following steps;

1) Define the problem frame
2) Identify key agents
3) Quantify the number of agents of each type
4) Determine (theoretically) how agents act in isolation and in response to other agents
5) Determine characteristic properties to explain majority of the behaviour
6) Map decision process (strategies)
7) List assumptions
8) Verify model design (subject matter experts)
9) Begin model development, use incremental procedure and test after each increment
10) Validate model functionality

The first three items have been discussed in the previous two chapters. The problem frame is the environmental impact at the system-of-systems level and how it is influenced by the introduction of novel technologies. As a study case aviation is considered as discussed in Section 1.2 . The number of agents is yet to be determined however they are defined by the stakeholder definition formulated in Section 2.2.3. The items 4-7 describe the considerations on the formulation of the internal models which will be described in the next section. Items 8-10 will limit the predictive capability of the model. In particular the approach of “growing” the model by adding elements with increased understanding is adopted as the main approach in the illustrative examples.

3.1.2 Modelling agent behaviour

The previous section discussed the elements present in an agent-based simulation framework. In particular the internal model of the agent should represent the stakeholder behaviour. In order to capture this in a mathematical form, the assumption for goal driven behaviour is made. This allows the selection of utility, as the measure for achievement of a certain goal, using a strategy. Utility allows the ranking of various strategies and allows the agent to select the strategy maximizing utility. The mathematical representation describing the response of the stakeholder/agent towards their preferences, desires and/or wants is called the utility function. In line with Hazelrigg[71, 72] utility and utility function are defined by:

> *utility is any quantitative scalar measure defined by a single rational stakeholder whose purpose is to rank order alternatives. The utility function is the set of utilities attributed to each of the products by the rational stakeholder.*

The difference between utility and value is consequently that product value is based on multiple stakeholder utilities, which is a non-trivial procedure as illustrated by Hazelrigg[72]. Novel technologies have been identified as enablers of behaviour. In this context the effects of a technology on the strategies and goals are discussed. Finally the incorporation of strategic decision making is discussed using game-theory.

Goal driven behaviour

In order to implement the complex inference of decision making into a mathematical form it is assumed that each stakeholder has a limited set of strategies, i.e. options to select from,

$$S = [s_1, s_2, \ldots, s_n] \tag{3.1}$$

Furthermore, they are assumed to be goal driven decision makers, i.e. their decision and resulting behaviour are intended to reach a goal. Each strategy can be attributed a numerical value for fulfilment of the goal, stakeholder *utility*

$$U = [u_1(s_1), u_2(s_2), \ldots, u_n(s_n)] \tag{3.2}$$

This translation is based on the internal model of the agent representing the stakeholder. It is assumed that the agent selects the utility which maximizes the fulfilment of the goal,

$$B = \max_S U(S). \tag{3.3}$$

The achievement of the goal, $u_n(s_n)$, is a function of the specific strategy s_n and the environment E at the time of the decision. Due to the possibility of limited information this E is limited to e_i, or the information as perceived by the stakeholder. The decision is performed at a certain event scheduled by the ABE as discussed in the previous section. The chosen and performed strategy is denoted behaviour of the agent. The maximization of utility, translated into the goal, by selecting and executing the appropriate strategy is considered to capture the rational[167] stakeholder behaviour. These definitions are summarized in Table 3.1. The previous mathematical treatment is simplified with respect to real behaviour.

Table 3.1: Definitions employed for the representation of stakeholders.

Goal	the objective or aim of the stakeholder
Strategy	a strategy in the game-theoretic context is a finite set of options available to the stakeholder, from which one is to be chosen to achieve the goal.
Behaviour	In this context behaviour is therefore the procedure of selection and execution of the strategy in order the achieve the objective of the stakeholder.

It implicitly assumes that the goal can be identified and quantified. This is hampered by the fact that goals can change over time, and might not even be explicitly known to the stakeholder. As an example, goals and strategies might change due to the introduction of a novel technology. Furthermore, the previous consideration is based on the ability to transform each strategy s_n for a given e into a utility u_n. This is not trivial and requires the quantification of, the complex process of inference leading to the stakeholder decision.

Consequently, if the stakeholder goal and its strategies can be identified and represented in a computational form, in principle the internal model of the agent representation can be implemented. In particular the translation of the strategies in the perceived environment is a complex task and subject to transformation errors. The concept of the rational stakeholder, assumes that the stakeholder can correctly translate its goals and needs into product attributes, which is generally not the case[35]. Corrections for this non-rational behaviour are presented by *bounded rationality*[168], limiting the number of options considered, and selecting acceptable alternatives from previous experiences. The influence of this limited rationality can be significant as indicated by the revenue generated from impulse shopping[28]. The influence of this limited rationality is considered small in business to business transactions, but poses a significant contribution in person to person interactions.

In conclusion, the imperfect translation from strategy into goal achievement employed by the stakeholder has to be captured in mathematical form in order to emulate the behaviour of the stakeholder. The previous considerations show the difficulty and importance of a correct understanding of the customers goals, their time and situation specific nature and their inherent change. All are critical for a proper prediction of stakeholder behaviour and as a consequence also for the prediction of system-of-systems properties.

Effect of technology on behaviour

As argued in the first chapter, novel technologies invalidate the *ceteris paribus* condition. Each technology supports the stakeholder, to a certain extent, in achieving this goal. The technology, implemented in a system, is therefore seen as a behaviour enabler. The technology might enable different strategies as well as enable different goals. The former alters or extends the set of strategies employable by the stakeholder, whereas the latter changes the transformation function u_n. Finally, the changing goals might be achieved by different strategies as well. As a consequence two types of goals and strategies can be identified; known and unknown ones. Focussing on changes due to technology, both alternative goals, e.g. sustainable operation, as well as alternative strategies, e.g. continuous descent approaches, might arise. The previous considerations have been schematically depicted in Figure 3.5, where the circle is the focus of current implementation, with extrapolations to yet unknown strategies and goals. The black arrows are considered to be, at least partly, identifiable. The dashed arrow is considered to be out of reach. Nevertheless, being aware of the limitations of the internal model emulating stakeholder behaviour is considered important knowledge for decision making based on the simulation results.

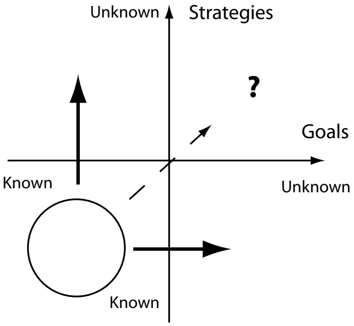


Figure 3.5: Relation of strategies and goals.

Effect of behaviour on technology

The design of a novel technology is also part of the set of strategies of a manufacturer. The QFD framework of the previous chapter is part of the behaviour displayed by the manufacturer. In this framework the effect of behaviour on the technology is identified. This goal driven behaviour is used in the identification of requirements and the formulation of the objective function and constraints from systems engineering[74]. In this approach the designer tries to identify the market segment — customer, function, technology — the product is going to target. In essence this involves identifying the particular area, country or section of the population that might value and consequently acquire the product as well as their motives for doing so. These motives might relate to enabling alternative strategies or goals, as well as improving the performance of current goals and strategies. Consequently the systems engineering approach focuses more on the goals and resulting needs of the potential customer, which can be fulfilled by the product.

Since the utility of the product is considered proportional to the amount of customers choosing the product from a set of alternatives, discrete choice analysis and the concept of utility have been investigated as potential mathematical representations of product value. *Discrete choice analysis* investigates the relation between product attributes and the choice made by the stakeholder. The non-uniqueness of the utility scales derived from this analysis poses a challenge to the development of novel competitive products as addressed in Appendix A.

Game theory

The previous section considered the investigation and quantification of utility of the various strategies and the resulting behaviour in isolation. The desirability of the strategy, i.e. the expected utility, might be influenced by the other stakeholders interacting with the stakeholder evaluating a strategy. To investigate the impact of this interaction and the identification of the best strategy, game theory is employed. Game theory is attributed to Neumann[105, 119, 126] and originated from the evaluation of board games. Game theory focuses on decision making, i.e. strategy selection, in either cooperative, non-cooperative and mixed games[105]. Design can be characterized as a cooperative game, as cus-

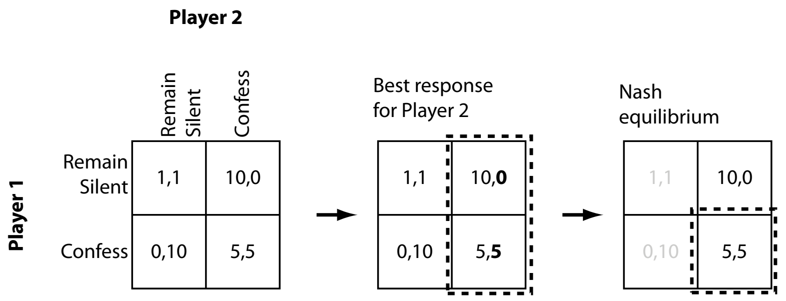


Figure 3.6: Example pay-off matrix for the prisoners dilemma. Illustrating both strategies and pay-off values. Pay-off equals years in prison (player 1, player 2), Defect means remain silent and cooperate means confess.

tomer and manufacturer both benefit creating a product suited to their needs. However, in the environment of airline competition non-cooperative games dominate. This affects the behaviour of the stakeholders directly as will be illustrated by a classical example of a non-cooperative game.

The simplest form of a game is a two-player game, where each player has two options, i.e. two strategies

$$\begin{aligned} S_1 &= [s_{11}, s_{12}] \\ S_2 &= [s_{21}, s_{22}] \end{aligned}$$

Assume that both players take their decision for a certain strategy simultaneously for a single round. This results in four possible plays, $[s_{11}, s_{21}], [s_{11}, s_{22}], [s_{12}, s_{21}], [s_{21}, s_{22}]$, where each *play* is the complete sequence of strategies chosen by each player. Assume that each play results in a certain pay-off for each player. Combined with the strategies this can be represented in a pay-off matrix, where the pay-off is equivalent to the utility defined in the previous section.

A classical non-cooperative game devised to illuminate the cold war dilemma is the non-cooperative prisoners dilemma[119]. It has also been characterized as a study of self-interest versus common-interest behaviour and could therefore be considered representative for the effect of human behaviour on environmental impact (externalities). The prisoners dilemma in its simplest form is given in Text-box 3.1 and its pay-off matrix is shown in Figure 3.6. Each of the elements in the matrix represents the years in prison for player 1 and player 2 (p1,p2) for choosing a certain strategy (Defect, Cooperate). In this game the pay-off (years in prison) is directly influenced by the choice of the other player. Before choosing both players try to minimize the number of years in prison by choosing the best strategy. This best strategy can be identified by evaluating the response of each competitor on a combination of strategies. Considering the response of player 2 to player 1 selecting “remain silent”. Choosing ”remain silent” would result in 1 year of imprisonment, “confess” would result in no imprisonment. Hence player 2 would select “confess”. The response of player 2 to player 1 selecting “confess” would be to “confess” as well with pay-off 5 years in prison. Consequently, player 2’s best action is independent on what player 1 selects: “confess”. Player 1 performs the same analysis and arrives at the same conclusion, that it is in his own best interest to confess. This results in an equilibrium (both confess), where

Prisoners dilemma

Two suspects are arrested by the police. The police have insufficient evidence for a conviction, and, having separated the prisoners, visit each of them to offer the same deal. Each suspect is offered a choice, either *cooperate* (confess), or *defect* (remain silent). Four possibilities arise, shown in Figure 3.6. If both suspects defect, they are only charged with minor charges, if either of them cooperates the other receives maximum penalty and the cooperator goes free. Finally if both cooperate they both get a reduced sentence. Assuming that they do not interact and the decision has no future consequences outside the game, what would be the best action for each suspect?

Text-box 3.1: Prisoners dilemma: originally by M. Flood and M. Dresher and formalized by A.W. Tucker.

both players cannot improve their value by a single sided change in strategy. This concept is formalized by Nash[124], who identified the non-uniqueness and stability of this equilibrium. The other interesting part of this game is how information can affect the decision.
If both players are aware of the underlying theory they are likely to remain silent as this is the best overall optimal strategy for the both players. However, as soon as one player confesses, the other should confess as well. If both players can agree to remain silent (information) they can coordinate to achieve this best pay-off of only one year in prison. Reinterpreting as the externalities description: without communication/agreement on the strategy, each individual chooses the option in its own best interest (pollute), which is different from the overall optimum (sustainable environment). To create a game where the individual strategy is in line with the best group strategy can be achieved by communication or changing the game pay-off. One example would be to penalize the individual best option (confess) more, with 2 years of imprisonment instead of 0 years.

In general stakeholders decisions and strategies are not limited to single move games. Depending on the number of moves and strategies, the information available might be limited depending on the memory of the player. This affects the strategy chosen by the stakeholder, varying from single stage strategies, limited to information in the decision stage, to complete information sets[105]. Furthermore, the prisoners dilemma is based on simultaneous decision making. However the sequence of making decisions can affect the outcome, consider for example the rock-paper-scissors game, where it is advantageous to move last.

In conclusion, the best strategy to be selected by competing stakeholders is often different from the isolated best strategy. The concept of utility can be used to identify the best strategies of both the decision maker and its competitors. In particular in the competition between stakeholders, e.g. manufacturers and airlines, this consideration of the competitors best strategy is important. Finally, only a limited set of the tools available to game theory, and situations of interest are discussed here to illustrate the basic principles. A more detailed introduction is given by Luce and Raiffa[105].

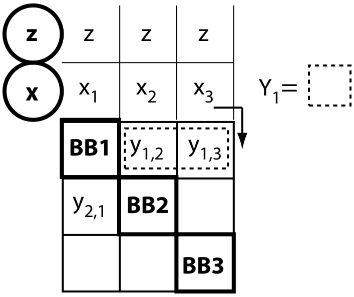


Figure 3.7: Variable definitions as used in the BLISS framework.

3.2 Bi-Level Integrated Systems Synthesis

The MDO problem as formulated by Equation 2.3 is addressed by the Bi-Level Integrated System Synthesis (BLISS) multidisciplinary optimization framework proposed by Sobieski, Agte and Sandusky[171]. In particular the multi-level approach is considered advantageous in the percentage of resources attributed to the actual design and improvement of the system. The BLISS framework assumes that the system can be described by a set of sub and/or aspect systems which are implemented in computational modules, i.e. disciplinary models. These modules are assumed to sufficiently describe and characterize the system in the conceptual design stage. For the current treatment, the modules are considered to be first principle methods combined with empirical models. Furthermore, it is considered that the MDO problem has been formulated from the requirements and constraints as well as the model induced constraints,

$$\begin{aligned} \min_{\boldsymbol{x}_D} \quad & \phi(\boldsymbol{x}_D, \boldsymbol{x}_E) \\ \text{s.t.} \quad & \boldsymbol{G}(\boldsymbol{x}_D, \boldsymbol{x}_E) \leq \mathbf{0} \end{aligned} \tag{3.4}$$

The system is described using n — mutually exclusive — modules representing various aspect or subsystems required to sufficiently characterize the system. Graphically these are represented in the design structure matrix (DSM) in Figure 3.7. The dependent variables $\boldsymbol{y}$ are defined as the variables providing the dependencies between the modules. Furthermore the independent variables $\boldsymbol{x}_D$ are subdivided into $\boldsymbol{x} = \bigcup_{i=1}^{n} \boldsymbol{x}_i$, design variables only used in a single module, and $\boldsymbol{z}$, design variables used in at least two modules.

As a consequence, the single valued objective function is rewritten as $\phi(\boldsymbol{x}, \boldsymbol{y}(\boldsymbol{x}, \boldsymbol{z}), \boldsymbol{z})$ and the model design space is constrained by $\boldsymbol{G}(\boldsymbol{x}, \boldsymbol{y}(\boldsymbol{x}, \boldsymbol{z}), \boldsymbol{z}) \leq \mathbf{0}$, resulting in

$$\begin{aligned} \min_{x,z} \quad & \phi(\boldsymbol{x}, \boldsymbol{y}(\boldsymbol{x}, \boldsymbol{z}), \boldsymbol{z}) \\ \text{s.t.} \quad & \boldsymbol{G}(\boldsymbol{x}, \boldsymbol{y}(\boldsymbol{x}, \boldsymbol{z}), \boldsymbol{z}) \leq \mathbf{0} \end{aligned} \tag{3.5}$$

The purpose of this redefinition of the problem is to distribute the optimization tasks over two levels; 1) the module or black box level, and 2) the system level, while maintaining a consistent design. The module level optimization controls the values for $\boldsymbol{x}_i$ whereas the system level optimization controls the values for $\boldsymbol{z}$. The formulation of each of the sub-optimizations is discussed in the first section.

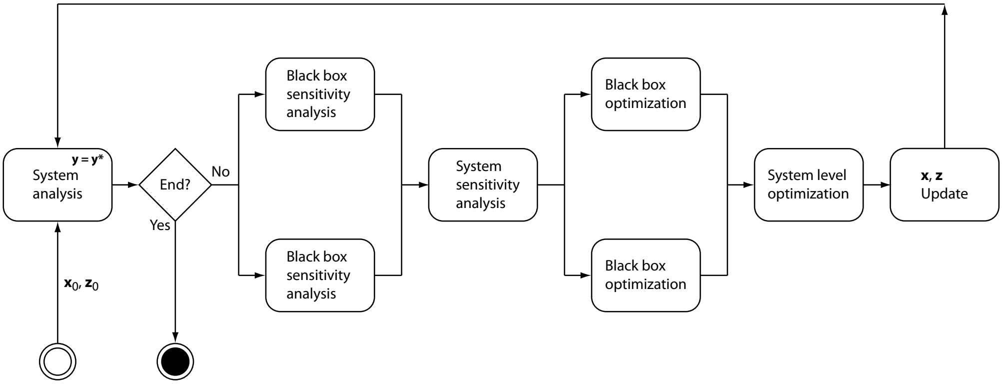


Figure 3.8: BLISS/B Flow chart, adapted from Sobieski[171]

3.2.1 Solution strategy

The overall iterative BLISS implementation is shown in Figure 3.8. The procedure starts by initiating the $\boldsymbol{x}$ and $\boldsymbol{z}$ variables and performing an (iterative) analysis procedure through all black boxes to obtain a consistent design, i.e. **System analysis**. From this consistent — not necessarily feasible, but computable — design, the finite differences are calculated for each of the black boxes in the **Black box sensitivity analysis**. These computations can be performed concurrently since they are independent of the overall system behaviour. The results are used to determine the global sensitivity equations (GSE[174]) needed to create the linearized objective function and determine the sub-optimization problem for each of the black boxes, i.e. **System sensitivity analysis**. Each of the black boxes is optimized in the **Black box optimization** with respect to its own surrogate optimization problem using the local independent variables, $\boldsymbol{x}_i$. The result of this optimization provides a more optimal set of local variables and a set of active constraints, denoted by the Lagrangians. These Lagrangians are used to create the surrogate system level objective function which is optimized for the system variables, $\boldsymbol{z}$, i.e. **System level optimization**. Two flavours of this system level optimization exist, BLISS/A and BLISS/B, both will be touched upon in the system optimization paragraph. The variables $\boldsymbol{x}, \boldsymbol{z}$ are replaced with the "improved" variables and the loop is repeated. The **End** criterion can be either a convergence criterion, e.g. no state or objective change, or a "no solution found" situation.

3.2.2 System analysis

The system analysis is an iterative procedure performed over all the black boxes to achieve a consistent design,

$$\boldsymbol{y} = \boldsymbol{y}^*. \tag{3.6}$$

This iterative procedure emerges once a feedback loop is present in the black box couplings. Taking the example in Figure 3.7, BB1 is coupled to BB2 by y_{12} and BB2 is coupled to BB1 by y_{21}. To solve this coupled set of black boxes an iterative procedure is required to obtain a consistent solution, i.e. y_{12}, y_{21}.

3.2.3 Black box optimization

The basis of BLISS is the specification of an objective function for each discipline. Each discipline is implemented in a disciplinary model and treated as a black box. Define black box BB1 as a module where the input is defined by $\boldsymbol{x}_1, \boldsymbol{y}_{i,1}, \boldsymbol{z}$, where subscript i denotes the black box origin of the dependent variable. The output of the black box is denoted $\boldsymbol{y}_1$. If dependent variables $\boldsymbol{y}$ in the black box come from various black boxes the vector $\boldsymbol{y}_{i,1}$ consists of elements from the compound output vector of all black boxes, $\boldsymbol{y} = [\boldsymbol{y}_2, \boldsymbol{y}_3, \ldots, \boldsymbol{y}_n]$. These definitions for the variables are given in Figure 3.7.

Assume that the objective function can be written as a first order Taylor series,

$$\phi = \phi(\boldsymbol{x}_0, \boldsymbol{y}(\boldsymbol{x}_0, \boldsymbol{z}_0), \boldsymbol{z}_0) + \sum_{i}^{n} \sum_{j} \mathrm{D}(\phi, x_{i,j}) \Delta x_{i,j} \tag{3.7}$$

The latter part of the linearized objective function gives an objective function for the black box i contributing to the "synthetic" system objective function with each local independent variable $x_{i,j}$, instead of discipline specific targets like drag or structural weight[171]. Consequently the black box optimization problem for black box i can be written as,

$$\begin{array}{ll} \min\limits_{\Delta \boldsymbol{x}_{i,j}} & \sum_j \mathrm{D}(\phi, x_{i,j}) \Delta x_{i,j} \\ \text{s.t.} & \quad \boldsymbol{G}_i \leq \boldsymbol{0} \end{array} \tag{3.8}$$

For given $\boldsymbol{x}_{i,j}, \boldsymbol{y}_{.,i}$ and $\boldsymbol{z}$, where $\boldsymbol{y}_{.,i}$ are the dependent input variables for the discipline. The element which is missing is the total derivative $\mathrm{D}(\phi, x_{i,j})$. Using the Global Sensitivity Equations (GSE)[174] this total derivative $\mathrm{D}()$ can be derived from the partial derivative $\mathrm{d}()$ according to,

$$\boldsymbol{A} \mathrm{D}(\boldsymbol{y}, x) = \mathrm{d}(\boldsymbol{y}, x) \tag{3.9}$$

where $\boldsymbol{A}$ is a square matrix composed of identity matrices and black box sensitivities,

$$\boldsymbol{A} = \begin{bmatrix} \boldsymbol{I} & \boldsymbol{A}_{1,2} & \ldots & \boldsymbol{A}_{1,N} \\ \boldsymbol{A}_{2,1} & \boldsymbol{I} & \ldots & \\ \ldots & & & \end{bmatrix}. \tag{3.10}$$

and element $\boldsymbol{A}_{i,j}$ is composed of partial derivatives of the form

$$\boldsymbol{A}_{i,j} = \begin{bmatrix} -\frac{\partial y_{i,1}}{\partial y_{j,1}} & -\frac{\partial y_{i,1}}{\partial y_{j,2}} & \cdots \\ -\frac{\partial y_{i,2}}{\partial y_{j,1}} & -\frac{\partial y_{i,2}}{\partial y_{j,2}} & \cdots \end{bmatrix}, \tag{3.11}$$

where $i \neq j$. i, j are the indices of the black boxes (to,from respectively) and the second index is the element index in vector $\boldsymbol{y}_{i/j}$. The computation of this matrix is resource intensive as a finite difference approach is used to allow for a true black box approach. In order to reduce computation time the elements in y_j which are not used as input in i are not computed as they result in $\frac{\partial y_{i,.}}{\partial y_{j,.}} = 0$.

3.2.4 System optimization

The black box optimization only addresses the impact of the local variables $\boldsymbol{x}$ on the objective function. Further improvement is to be achieved by manipulating the system variables

$\boldsymbol{z}$. In order to improve the system, the total derivative of the objective function with respect to the global $\boldsymbol{z}$ variables is needed.

BLISS/A BLISS/A uses the GSE, however since the BB optimization returns its optimization result ($\boldsymbol{x}$) as a function of $\boldsymbol{z}$, this dependency has to be accounted for. Equation 3.9 consequently takes the following form[171, 172],

$$\boldsymbol{M}\begin{bmatrix} \mathrm{D}(\boldsymbol{y}, z) \\ \mathrm{D}(\boldsymbol{x}, z) \end{bmatrix} = \begin{bmatrix} \mathrm{d}(\boldsymbol{y}, z) \\ \mathrm{d}(\boldsymbol{x}, z) \end{bmatrix} \tag{3.12}$$

The derivatives $\mathrm{d}(\boldsymbol{y}, y), \mathrm{d}(\boldsymbol{y}, x), \mathrm{d}(\boldsymbol{y}, z)$ can be determined as before in the black box sensitivity analysis. The derivatives $\mathrm{d}(\boldsymbol{x}, z), \mathrm{d}(\boldsymbol{x}, y)$ are determined by investigating the sensitivity of the black box optimum found for the given $\boldsymbol{z}$ and $\boldsymbol{y}$ variables. This if done by perturbing the parameter of interest by a small increment, $\Delta z, \Delta y$ and solving the extrapolated optimization problem. The new optimum found gives the derivative by

$$\mathrm{d}(\boldsymbol{x}, [z, y]) = (\boldsymbol{x}_{extr} - \boldsymbol{x}_{[y,z]})/\Delta[z, y], \tag{3.13}$$

where $extr$ is the extrapolated optimization result and $[y, z]$ the parameter of interest for the derivative calculation.

BLISS/B In the BLISS/B flavour the system optimization is considered to be constrained by the black box constraints (linearized about the current state)

$$\mathrm{D}(\phi, \boldsymbol{z}) = \sum_{i=1}^{n} \boldsymbol{L}_i \mathrm{d}(\boldsymbol{G}, \boldsymbol{z})_i + \mathrm{D}(\boldsymbol{y}, \boldsymbol{z}) \sum_{i=1}^{n} \boldsymbol{L}_i \mathrm{d}(\boldsymbol{G}, \boldsymbol{y})_i + \mathrm{d}(\phi, \boldsymbol{z}) \tag{3.14}$$

Where $\boldsymbol{L}_i$ is the vector of Lagrange multipliers obtained from the black box optimizations. The total derivative, $\mathrm{D}(\phi, \boldsymbol{z})$ is a constrained derivative protecting $\boldsymbol{G} = \boldsymbol{0}$ for all black boxes, $i = 1..n$. The total derivative $\mathrm{D}(\boldsymbol{y}, \boldsymbol{z})$ is computed in a similar fashion using Equation 3.9, but replacing x with z. However, constraints at the system level might exist. Where these constraints are subject to limited influence from black box variables $\boldsymbol{x}$, but determined by the system variables $\boldsymbol{z}, \boldsymbol{y}$. The system optimization consequently becomes,

$$\begin{aligned} \min_{\Delta \boldsymbol{z}} \quad & \mathrm{D}(\phi, \boldsymbol{z})\Delta \boldsymbol{z} \\ \text{s.t.} \quad & \boldsymbol{G}(\boldsymbol{y}, \boldsymbol{z}) \leq \boldsymbol{0} \end{aligned} \tag{3.15}$$

Furthermore, both $\boldsymbol{z}$ and $\Delta \boldsymbol{z}$ are constrained by so called move limits, to prevent too large deviations from the actual states by the linearized problem. The implementation of this framework is considered in Chapter 6, using the design of a blended wing body as a guideline.

3.3 Bayesian inference

To address the modelling complexity identified in Chapter 2, a probabilistic treatment is required. In order to estimate the error, consider that each model assumes a certain relation

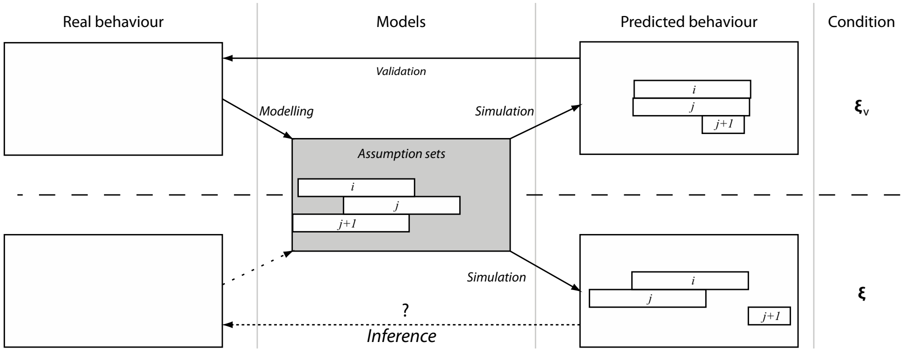


Figure 3.9: Theoretical framework of model creation, assumption sets and their impact on the predicted behaviour.

between variables, called assumptions, which need not exist in nature [52]. A useful model removes all unnecessary details to provide clear picture of the studied phenomenon[116]. Since a model is required to predict behaviour, the variable of interest is by definition a dependent variable y. The model prediction of this dependent variable is affected by the appropriateness of the assumptions. Model errors exist, both in the existence of relations (dependent/ independent variable) and the mathematical implementation of these relations. The former draws the attention to the validity of the internal structure of the model (conceptual model) and the latter to the mathematical relations in the model (mathematical model). In particular the predictive model capability inferred from a model input with known error, $\boldsymbol{\xi}_v$ to a model input of interest $\boldsymbol{\xi}$

$$\epsilon_m(\boldsymbol{\xi},\boldsymbol{\xi}_m) = \epsilon_m(\boldsymbol{\xi}_v,\boldsymbol{\xi}_{m_v}) + \Delta\epsilon_m(\boldsymbol{\xi_v},\boldsymbol{\xi},\boldsymbol{\xi}_m,\boldsymbol{\xi}_{m_v}) \tag{3.16}$$

This concept is shown schematically in Figure 3.9. Here *modelling* is defined as the procedure to derive principles from the real world and capture or code them into mathematical or conceptual models and *simulation* is the procedure of using these models to determine the parameter of interest for a model input, which can be different from the input used to derive the model. *Validation* compares the result of simulation to the real world behaviour in order to determine the applicability and validity, i.e. error, of the model for input $\boldsymbol{\xi}_v$[158]. However, the behaviour of interest, and consequently the error produced by the model is required for input condition $\boldsymbol{\xi}$. A prediction of this behaviour can be produced by various models, each based on their own assumption sets, i, j, k, which can be evaluated for both inputs $\boldsymbol{\xi}_v, \boldsymbol{\xi}$. The additional information stemming from the various models is used in order to estimate the model form error. First a closer look is taken at this error and a method is devised for combining the information of various models. Subsequently, methods to approximate this error are discussed. This approximation is extended using a probabilistic approach to address the introduced uncertainty. Finally, these considerations on physical phenomena are applied qualitatively to the behavioural models proposed for the ABMS approach.

3.3.1 Model form error

The model form error is mainly determined by the model assumptions. The assumptions limiting the state vector $\boldsymbol{\xi}$ to the model state vector $\boldsymbol{\xi}_m$ are the most readily observed. In this case, the unconsidered state variables are assumed equal to the implicit model values, or alternatively limited in influence on the dependent variable. To determine whether the model predictions can be used for inference is therefore considered equivalent to determining whether the assumptions underlying the model are applicable. Furthermore, focussing on the underlying assumptions instead of model validity prevents attributing too much trust into overlapping models.

Consider that an assumption basically is a restriction on the relation between possible relations of the real state. Mathematically an assumption can be written as a fixed relation between real condition describing variable,

$$\text{assumption}; f(\boldsymbol{\xi}) = c. \tag{3.17}$$

If condition $\boldsymbol{\xi}$ is equal to the condition implied by the model assumption, the states are considered comparable. However, if this is not the case, the impact of this assumption on the parameter of interest, r, should be investigated. These assumptions determine the model form error and are treated by looking at the difference in real and model response. Assuming $\epsilon_n = 0$ and $\epsilon_{exp} = 0$ in Equation 2.12, and rewriting for the model form error gives

$$\epsilon_m(\boldsymbol{\xi}) = r(\boldsymbol{\xi}) - m(\boldsymbol{\xi}_m). \tag{3.18}$$

For design, the interest lies on the difference between the real system response $r(\boldsymbol{\xi})$ for condition $\boldsymbol{\xi}$ compared to a model response $m(\boldsymbol{\xi}_m)$. However, often evidence is available for condition $\boldsymbol{\xi}_v$. As proposed by Equation 3.16, from $\boldsymbol{\xi}_v$ an extrapolation is made to $\boldsymbol{\xi}$. Assuming that the real system responses exist along a piecewise continuous path $\mathcal{C}$, this error $\epsilon(\boldsymbol{\xi})$ can be related to the impact at state $\boldsymbol{\xi}_v$ by,

$$\epsilon_m(\boldsymbol{\xi}) = \epsilon_m(\boldsymbol{\xi}_v) + \int_{\mathcal{C}} \nabla \left(r(\boldsymbol{\xi}) - m(\boldsymbol{\xi}) \right) \cdot \mathrm{d}\boldsymbol{\xi} \tag{3.19}$$

Since — by definition — the function in the integral is conservative, the chosen path from $\boldsymbol{\xi}_v$ to $\boldsymbol{\xi}$ has no influence on the outcome of the integral. It is assumed that information on the impact of model assumptions is more easily obtained than overall system behaviour, e.g. “is the flow turbulent” versus “is the drag prediction within the acceptable range”, as well as the the effect of this assumption. Consider a model m with F known assumptions,

$$f(\boldsymbol{\xi})_i = c_i, \; i = 1..F \tag{3.20}$$

The error introduced by a single assumption is determined by,

$$\left(\epsilon_m(\boldsymbol{\xi}) - \epsilon_m(\boldsymbol{\xi}_v)\right)_{f_i} = \int_{\mathcal{C}} \left(\frac{\partial r(\boldsymbol{\xi})}{\partial f(\boldsymbol{\xi})} - \frac{\partial m(\boldsymbol{\xi})}{\partial f(\boldsymbol{\xi})} \right) \nabla f(\boldsymbol{\xi}) \cdot \mathrm{d}\boldsymbol{\xi} \tag{3.21}$$

since the model has the assumption incorporated the model derivative with respect to the assumption equates to zero, giving,

$$\left(\epsilon_m(\boldsymbol{\xi}) - \epsilon_m(\boldsymbol{\xi}_v)\right)_{f_i} = \int_{\mathcal{C}} \frac{\partial r(\boldsymbol{\xi})}{\partial f(\boldsymbol{\xi})} \nabla f(\boldsymbol{\xi}) \cdot \mathrm{d}\boldsymbol{\xi} \tag{3.22}$$

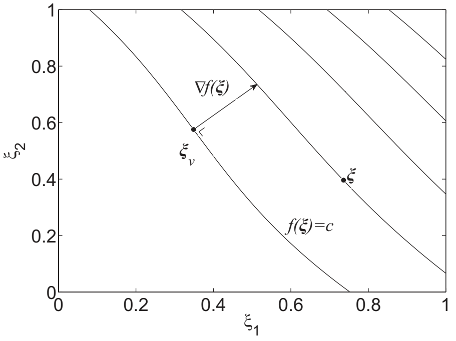


Figure 3.10: Schematic representation of assumption contours and the path perpendicular to the assumption.

which again is a conservative integral and the resulting error estimate is independent of the path taken. Now the assumption induced error can represented as a path from a contour $f(\boldsymbol{\xi}) = c$ containing state $\boldsymbol{\xi}_v$ to the contour containing $\boldsymbol{\xi}$, with the error of each point of this contour defined by the derivative of the response with respect to the assumption. The error consists of a distance, and error per distance. Distance is defined as the length of the shortest path between two contours of constant $f(\boldsymbol{\xi})$, from the state $\boldsymbol{\xi}_v$ to the state of interest $\boldsymbol{\xi}$, i.e. perpendicular to the assumption as indicated in Figure 3.10. Since no information is available on the development of the real response with respect to the assumption, as a general rule,

> *The larger the distance from the model derivation area to the area of interest the larger the uncertainty in the error of an assumption and consequently the model error.*

Since no measurements have been performed there is no certainty that the assumption has a large impact on the parameter of interest, but it is more likely.
The model form error consists of a combination of all assumption errors. In order to combine these errors, if the set of assumptions is complete and all assumptions are orthogonal, where orthogonality is defined by

$$\int_{\mathcal{C}} \frac{\partial r(\boldsymbol{\xi})}{\partial f(\boldsymbol{\xi}_i)} \nabla f(\boldsymbol{\xi})_i \cdot \frac{\partial r(\boldsymbol{\xi})}{\partial f(\boldsymbol{\xi})_j} \nabla f(\boldsymbol{\xi})_j \mathrm{d}\boldsymbol{\xi} = 0,\ i = 1..F,\ j = i+1..F \tag{3.23}$$

the total error can be determined by performing a summation over the assumption errors,

$$\epsilon_m(\boldsymbol{\xi}) - \epsilon_m(\boldsymbol{\xi}_v) = \sum_i \left(\epsilon_m(\boldsymbol{\xi}) - \epsilon_m(\boldsymbol{\xi}_v)\right)_{f_i} \tag{3.24}$$

If the assumptions are found not to be orthogonal, they have to be rewritten to form an orthogonal basis in order to facilitate the above considerations, or as a first indication orthogonallity can be assumed. This assumption of orthogonallity is at the risk of double counting error effects.

In conclusion, if the impact of assumptions on the real response is known, a prediction can be made of the model impact in state $\boldsymbol{\xi}$, based on state $\boldsymbol{\xi}_v$. However, the real response is generally not available. In order to address this, a decomposition and recombination method is provided, as well as a means of considering incompleteness of assumptions. Completeness is not achievable due to the infiniteness of the concept description vector and its influences. Nevertheless, the designer has to explicitly consider the incompleteness in terms of assumption influence on the response parameter of interest, r.

3.3.2 Approximating assumption impact

Returning to Equation 3.22, the derivative of the response with respect to the assumption is unknown on path $\mathcal{C}$ and has to be estimated. Besides assuming a constant value along its path,

$$\frac{\partial r(\boldsymbol{\xi})}{\partial f(\boldsymbol{\xi})} \approx \frac{\partial r(\boldsymbol{\xi}_v)}{\partial f(\boldsymbol{\xi}_v)} \tag{3.25}$$

an alternative would be to consider that each model is based on a different assumption set providing a different — but limited — view on the real behaviour. Consequently, given an additional model $m_j \neq m_i$, without assumption $f(\boldsymbol{\xi}) = c$, an estimate can be given of the response development perpendicular to this assumption,

$$\begin{aligned} \frac{\partial r(\boldsymbol{\xi})}{\partial f(\boldsymbol{\xi})} &\approx \frac{\partial m(\boldsymbol{\xi}_j)_j}{\partial f(\boldsymbol{\xi})} \\ \int_{\mathcal{C}} \frac{\partial r(\boldsymbol{\xi})}{\partial f(\boldsymbol{\xi})} \nabla f(\boldsymbol{\xi}) \cdot \mathrm{d}\boldsymbol{\xi} &= \int_{\mathcal{C}} \frac{\partial m(\boldsymbol{\xi})}{\partial f(\boldsymbol{\xi})} \nabla f(\boldsymbol{\xi}) \cdot \mathrm{d}\boldsymbol{\xi} + \epsilon_f \end{aligned} \tag{3.26}$$

the approximation is determined by the assumptions of model j, and as a consequence, an error distribution, ϵ_f on this error estimation has to be estimated. One could conclude that replacing one error, i.e. ϵ_m, with another, i.e. ϵ_f, has no benefits and is therefore not worth the effort. However, this inference allows for 1) the use of all information available to the designer and 2) provides a method of combining this information in order to have an understanding of the origins of possible errors, a means of determining their impact on the response of interest and 3) a means of making the subjective reasoning and its effects explicit. Nevertheless, without comparison of real world behaviour for $\boldsymbol{\xi}$ and $\boldsymbol{\xi}_m$ the actual error remains uncertain and a probabilistic treatment is required.

3.3.3 Probabilistic theoretical framework

Before continuing some notation is defined: capital letters define a complete set of events, e.g in case of two events $E = \{e, \neg e\}$, and small letters denote the possible events within this set. Consequently, for two sets $E = \{e, \neg e\}, R = \{r, \neg r\}$, $\mathcal{P}(E|R)$ denotes a matrix of conditional probabilities, consisting of four conditional probabilities; $\mathcal{P}(e|r), \mathcal{P}(\neg e|r), \mathcal{P}(e|\neg r)$ and $\mathcal{P}(\neg e|\neg r)$. Furthermore, if another set is added $F = \{f, \neg f\}$, $p(E, F|R)$ denotes a matrix consisting of the elements of the form, $\mathcal{P}(e \cap f|r), \mathcal{P}(e \cap \neg f|r), \ldots.$ And finally, $\sum_R$ means a summation over all elements in the set R.

Since the designer uses models which are a limited and abstracted view on reality, an assessment of their validity — capability to predict real behaviour — has to be performed.

In general, once an important uncertainty has been identified, new information is gathered to reduce this uncertainty. As a result, validity analysis should be updateable in light of this new information [68]. The previous reasoning has been formalized by Bayes [13] in his update scheme[1]

$$\mathcal{P}(r|E) = \frac{\mathcal{P}(E|r)\mathcal{P}(r)}{\mathcal{P}(E)} = \frac{\mathcal{P}(E \cap r)}{\mathcal{P}(E)} \tag{3.27}$$

which states that when observing evidence E the conditional probability $\mathcal{P}(r|E)$ can be updated. Therefore, the probability on r before the observation, $\mathcal{P}(r)$ is called the *prior*, and after observing event E, $\mathcal{P}(r|E)$ the *posterior* probability is derived. Bayes states that all probabilities are subjective in nature [13]. To represent this fact, F_0, i.e. the frame of discernment is introduced[2] which resembles the information considered by the designer. This frame of discernment is a subset of all hypothetical information $\Omega = \{F_0, \neg F_0\}$. The subjective Bayes relation becomes,

$$\mathcal{P}(r|E \cap F_0) = \frac{\mathcal{P}(E|r \cap F_0)\mathcal{P}(r|F_0)}{\mathcal{P}(E|F_0)} \tag{3.28}$$

explicitly stating that the probabilities are subjective in nature, i.e. limited to the considered information, but are updatable when new evidence becomes available. The impact of this frame of discernment on the probability can be identified: consider a hypothesis H_0 of which the probability of correctness is given by $\mathcal{P}(H_0)$, since the probabilities are considered subjective and limited to the frame of discernment, information is available on $\mathcal{P}(H_0|F_0)$. Given that Ω consists of two mutually exclusive elements, the probability can be written as,

$$\mathcal{P}(H_0) = \mathcal{P}(H_0|F_0)\mathcal{P}(F_0) + \mathcal{P}(H_0|\neg F_0)\mathcal{P}(\neg F_0), \tag{3.29}$$

which states that one has to assess the probability that the frame of discernment under consideration is the appropriate one, before being able to assess the probability on H_0. This makes the open world assumption explicit [40]. Rewriting in terms of the considered information $\mathcal{P}(H_0|F_0)$,

$$\mathcal{P}(H_0) = \mathcal{P}(H_0|F_0)\mathcal{P}(F_0) + \alpha(1 - \mathcal{P}(F_0)), \tag{3.30}$$

where α is an unknown conditional probability, which is limited between zero and one. Applying these limits a lower, $\mathcal{P}()_*$, (Belief) and an upper probability, $\mathcal{P}()^*$ (Plausibility) can be formulated [169]:

$$\begin{aligned} \mathcal{P}(H_0)_* &= \mathcal{P}(H_0|F_0)\mathcal{P}(F_0) \\ \mathcal{P}(H_0)^* &= \mathcal{P}(H_0|F_0)\mathcal{P}(F_0) + 1 - \mathcal{P}(F_0) \end{aligned} \tag{3.31}$$

Design feasibility criterion

A general hypothesis under consideration can therefore be formulated as the probability that a parameter is within predefined limits;

$$\mathcal{P}(H_0) = \int_{r_*}^{r^*} \varrho(r)\mathrm{d}r \tag{3.32}$$

---

[1] Alternative update schemes are possible as indicated by Smets[169].

[2] The frame of discernment consists of all states considered by the designer. Consider a coin flipping experiment where the frame of discernment usually consists of heads and tails, however, loosing or breaking the coin might also be possible outcomes affecting the outcome.

where $\mathcal{P}(H_0)$[3] is the probability that the statement is true, r_* and r^* are the lower and upper limit of the desired response respectively, and $\varrho(r)$ the probability density function of the real system response r. The real system response is considered to be determined by the system state $\boldsymbol{\xi}$, which is defined as a vector of infinite length describing the real state of the system. The states are considered to be mutually exclusive for the current framework and consequently the integral over the states under consideration should be taken,

$$\mathcal{P}(H_0) = \int_{\boldsymbol{\xi}} \int_{r_*}^{r^*} \varrho(r|\boldsymbol{\xi})\varrho(\boldsymbol{\xi})\mathrm{d}r\mathrm{d}\boldsymbol{\xi}, \tag{3.33}$$

where $\varrho(\boldsymbol{\xi})$ can be interpreted as the probability such a state occurs or can be realized — within the project constraints. The Bayesian update scheme can be employed to gain insight in the probability on H_0, by updating $\varrho(\boldsymbol{\xi})$ or $\varrho(r|\boldsymbol{\xi})$ when evidence comes available. Since information is available in the form of models, the relation between the model predictions and the real response is of interest;

$$\mathcal{P}(r|\boldsymbol{\xi})\mathcal{P}(\boldsymbol{\xi}) \rightarrow \mathcal{P}(m|\boldsymbol{\xi}_m)\mathcal{P}(\boldsymbol{\xi}_m). \tag{3.34}$$

Given the various sources of model errors [106], combined into ϵ the relation between the real response and model prediction is given by

$$r(\boldsymbol{\xi}) = m(\boldsymbol{\xi}_m) + \epsilon(\boldsymbol{\xi}, \boldsymbol{\xi}_m) \tag{3.35}$$

which includes the model response in its considered and limited model state and the resulting discrepancy, due to model and state inconsistency. As a consequence, the probability on r in state $\boldsymbol{\xi}$ is given by

$$\mathcal{P}(r - m|\boldsymbol{\xi} \cap \boldsymbol{\xi}_m) = \mathcal{P}(\epsilon|\boldsymbol{\xi}_m \cap \boldsymbol{\xi}) \tag{3.36}$$

for a deterministic model the probability on r is given by the error probability distribution [89]. Within this error both the model incorrectness — inconsistent model and real response — as well as the state incorrectness — inconsistent model and real state — are captured.

Model error

Given a deterministic model, the probability that real behaviour r is within a certain range, given an — analytical — model result m, where $\epsilon_n = 0$, is determined by the error probability,

$$r(\boldsymbol{\xi}) \in m(\boldsymbol{\xi}_m) + [\epsilon_*, \epsilon^*] \Rightarrow r(\boldsymbol{\xi}) - m(\boldsymbol{\xi}_m) \in [\epsilon_*, \epsilon^*] \tag{3.37}$$

where ϵ_*, ϵ^* are the lower and upper bounds on the error respectively. The treatment of the difference in model and real state, $\boldsymbol{\xi}_m, \boldsymbol{\xi}$, states that the model and reality are comparing possibly different states. Since the model state is a vector of finite length and the real state a vector of infinite length, the probability that they are equal is determined by the probability that the values not considered in the model state are equal to the real state values. This makes the probability on equal model and real states almost surely zero[4].

---

[3] Upon implementation information on $\mathcal{P}(H_0|F_0)$ is available. For conciseness, this conditional is omitted from here on.

[4] The possibility of equal states exists but is infinitesimally small. Furthermore, each variable is essentially considered to be in an accuracy range, if the accuracy is increased, the probability becomes zero.

The result is that state equivalence is highly improbable and all state variables should be treated as assumption induced error, as discussed in Section 2.4.2. Due to the infinite length of the real state vector this is impossible, however, it shows the inherent limitations of each inference and the need for Equation 3.31. Furthermore, it forces the designer to make these implicit assumptions explicit and estimate their induced error.

To determine the probability whether model error ϵ_m is within a certain range $[\epsilon_*, \epsilon^*]$ for a given real and model state $\boldsymbol{\xi}, \boldsymbol{\xi}_m$, a new hypothesis H is formed,

$$H : \epsilon_m \in [\epsilon_*, \epsilon^*], \tag{3.38}$$

where the conditionality on the states is omitted. The probability on the validity of this hypothesis would be

$$\mathcal{P}(H) = \int_{\epsilon_*=r-m}^{\epsilon^*=r-m} \varrho(\epsilon_m)\mathrm{d}\epsilon_m, \tag{3.39}$$

which could be determined directly if information on probability distribution of the model error is available. Often, information is available with respect to the probability distribution of the error due to the assumptions. In Section 2.4.2 the relation between model and assumption-induced error is derived from state $\boldsymbol{\xi}_v$ to $\boldsymbol{\xi}$. Using this relation, for a complete set of orthogonal assumptions, the probability on the hypothesis can be written as,

$$\mathcal{P}(H) = \int_{-\infty}^{\infty} \cdots \int_{\epsilon_*-\sum_i \epsilon_i}^{\epsilon^*-\sum_i \epsilon_i} \prod_i \varrho(\epsilon_i)\mathrm{d}\epsilon_i, \tag{3.40}$$

which for three independent assumptions should be interpreted as,

$$\mathcal{P}(H) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{\epsilon_*-\epsilon_1-\epsilon_2}^{\epsilon^*-\epsilon_1-\epsilon_2} \varrho(\epsilon_1)\varrho(\epsilon_2)\varrho(\epsilon_3)\mathrm{d}\epsilon_3\mathrm{d}\epsilon_2\mathrm{d}\epsilon_1. \tag{3.41}$$

The result states that the assumptions can be used to estimate the (*prior*) probability on a certain error in state $\boldsymbol{\xi}$.
Using the method in Section 2.4.2, the designer has to estimate the error development along the path introducing a subjective uncertainty on the error. This treatment is substantiated in more detail in Chapter 8, using the Coandă vehicle as an example.

3.3.4 Application to behaviour models

The previous sections considered the limitations to capturing physical phenomena into mathematical representations. These limitations have an even more pronounced effect on the models underlying the agents emulating stakeholder behaviour. As discussed in Section 3.1, the basis of this behaviour is assumed to be (one of) the goal(s) of the stakeholder, which combined with the internal model determines the choice for a specific strategy. Two limitations are present in this modelling, 1) the inability to represent all stakeholders due to the lack of data and 2) the inability to represent stakeholder behaviour due to implementation limitations. Both will be discussed in the next paragraph. A qualitative method of addressing these shortcomings is proposed after which some final conclusions are drawn.

Agent model limitations

The incompleteness of data used to create agent models is generally caused by time and resource constraints on data acquisitions. As an illustration, the number of individual airlines to be considered with their individual internal models already requires 200+ agents not to mention the millions of passengers each year. To address this issue, a subsection of the general population — either organizations or people — is taken as being representative for the whole group. Errors due to this incompleteness are minimized by carefully selecting the people being interviewed and using statistical techniques. Consider as an example the geographical location of passengers and airlines, which greatly affects their behaviour. In particular the mature US market has been studied intensively. The largest growing market in Asia, on the other hand, has only limited information available.

The second limitation is caused by the computational approach taken by ABMS. Any computational agent model is limited in the stakeholder behaviour it can represent by the strategies implemented into the model. Real world behaviour on the other hand is not limited to this finite number of options. This is shown by human creativity continuously challenging the boundaries of "behaviour" by for instance enabling technologies. Using human actors in the loop might provide a solution in the form of serious gaming[14]. For large numbers of actors the coordination task becomes large and might even be unmanageable. Software frameworks allowing for human interaction in a virtual world are also limited by the actions allowed in this environment, even though this set of accommodated actions can be extended. The consequence is that not all stakeholders, either represented by an agent or human actor, can be taken into account and a selection has to be made. Consequently ABMS is inherently incomplete.

For the ABMS and internal agent models, the criterion is as posed by Miller and Page[116] adopted for the evaluation of the usefulness of the results:

> *Tools need to be judged by their ability to enhance scientific enterprise; theories need to be judged by how well they are able to improve our understanding of the world around us, and not by what tools we used to derive them.*

Proposed considerations on agent models

The analogy with the extrapolation of the mathematical model error from the validated condition ξ_v, i.e. current situation, to the condition of interest ξ, i.e. possible future state due to the introduction of the novel technology, is apparent. Consequently, the assumptions underlying these models and their influence, represented in 1) the zero influence of the unconsidered attributes and 2) the zero influence of the equal attributes, might also be treated using a similar framework. This drives the need for extrapolation of the mathematical representation from the current environment to the environment of interest, e.g. after introduction of the technology. However, the purpose of this thesis is to illustrate the complexities in sustainable design. Consequently, the choice is made to limit the discussion on this extrapolation of stakeholder behaviour to a qualitative one. Consequently, the extrapolation of agent behaviour is not performed in the ABMS environment, but requires the explicit implementation by the user. Nevertheless, the following discussion is required to illustrate the limitations of focussing on current behaviour and the difficulty of predicting stakeholder behaviour in response to novel technologies. The conditions for which the behaviour model is derived, *ceteris paribus*, is represented by the circle in Figure 3.11.

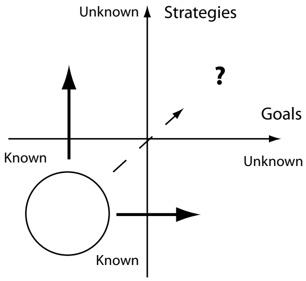


Figure 3.11: Relation of strategies and goals [Repeated from Figure 3.5].

The arrows represent alternative stakeholder behaviours, caused by an adaptation of goal, strategy or both. These goal and strategy changes are closely coupled to the stakeholder environment[9]. Possible changes in the environment — beside the introduction of the system under consideration — are changes in the layers of the system-of-systems — environment — 1) resources, 2) operations, 3) economics and 4) policies[42, 41]. Possible changes in all of these layers in the system-of-systems should be considered in the implementation of the stakeholder behaviour. In addition to this, creating scenarios might aid in the realism check on possible combinations of these changes and their effect on the stakeholder behaviour[159].

Concluding remarks

The pitfall of relying too much on behavioural models can be demonstrated by looking at one of the important attributes in aviation where symmetry occurs most of the time; safety. Due to this symmetry, safety is ranked relatively low on passenger responses[33, pp.60]. Its importance only becomes apparent once symmetry is broken, that is when — in the perception of passengers — safety is compromised. A second example is the development of the Dassault Mercure, which can be considered to be too focussed on a limited number of customers[133]. The result has been that this aircraft was designed[137, 194] based on an incorrect representation of the actual airline requirements. This latter example might also occur for novel aircraft configurations. The current aircraft fleet consists completely of tube-wing aircraft and share similar — possibly unconsidered and unknown — attribute values which result in indifferent valuations. Applying these valuations directly to the novel aircraft concepts might neglect key differences and incorrectly predict the customer decision.

Text-box 3.2: Effect of incorrect interpretation of behavioural models.

The previously identified model limitations result in a limited predictive capability and limited usefulness in the design. Consequently, carefulness should be employed when designing products to take advantage of these computational agent models as illustrated by the examples in 3.2. The incorrect interpretation of the stakeholder perceived utility caused by a lack of asymmetry in attribute values and the incorrect attribute valuations occurs for conventional technologies, but has an even more pronounced effect for novel technologies.

In particular in the context of preemptively considering, and designing for, the effect of the technology on the system-of-systems level environmental impact.

Despite the limited predictive capabilities, the ABMS framework provides tools to 1) test propositions, 2) investigate the effect of stakeholder interactions and 3) illustrate the effect of emerging behaviour in an artificial environment. Generalization from model results to real world conclusions requires careful interpretation of the model results within the bounds of the employed tools. This is addressed in more detail in Section 5.2. Nevertheless, the incomplete view provided by the models can provide important information on real world interaction, but inferences from these models should be treated with care.

3.4 Illustrative show cases

The tools proposed in this chapter span the set of complexities at the system-of-systems and system level. In particular each of the tools (ABMS, BLISS, Bayes) addresses one of the challenges posed in Section 2.5. Their combined results are required to determine the desirability of a technology. However, instead of applying a single technology to all three tools the choice is made to address a part of the broad scope of technologies proposed to aid in the reduction of environmental impact. This is done to illustrate the complexities in sustainable design, which are common to all these technologies. The suitability of these tools for addressing real world sustainability problems is illustrated using show cases in the next chapters.

Challenge 1

> The complexities at the system-of-systems level. In particular the modelling of stakeholders in a computational domain and the coupling of behaviour, technology and the resulting environmental impact.

For this challenge the ABMS approach is proposed. Chapter 4 describes the interaction of the stakeholders in a limited part of aviation. The complete set of stakeholders present in aviation is reduced to two markets for which the stakeholder interactions are studied from a myopic perspective. In Chapter 5, this myopic perspective is implemented in an ABMS framework and used to evaluate the environmental impact of MagLev technology. The direct link of the MagLev technology makes it an ideal candidate for illustrating the difference in system and system-of-systems level impact. This framework implementation is limited to predicting behaviour on the basis of previously portrayed behaviour. However, the MagLev technology is not mature enough to illustrate the challenges posed by human creativity. To illustrate the difficulty of predicting the volatile nature of human behaviour, the more mature Prandtl Plane (also known as the box-wing) is used.

Challenge 2

> The structural and behavioural complexity present in the conceptual design of a system, using an multidisciplinary design optimization framework

For this challenge the BLISS framework is proposed. To illustrate the application of the BLISS framework in the conceptual design, the challenge of the BWB is taken. Its closely intertwined components are a challenging example of the difficulty of finding a solution in the multidisciplinary design space. This challenge is addressed by the BLISS framework in Chapter 6.

Challenge 3

> The modelling complexity and in particular the uncertainty in model errors occurring for (novel) technologies

For this challenge the Bayes framework is proposed. The proposed method of MDO for addressing the behavioural and structural complexity at system level leans heavily on mathematical representations of real system behaviour. This introduces modelling complexity in the design problem, i.e. how well do the model predictions emulate real system behaviour. Chapter 7 illustrates this complexity using the validation of a potential model for the propeller-wing-empennage interaction as an example. This technology, although proposed as the most efficient means of propelling aircraft, is considered conventional. The additional challenges posed by a novel technology in model validation are illustrated using the design of a micro aerial vehicle (MAV), i.e. the Coandă plane in Chapter 8.

Relative complexity The measures of how well the show case represents the real world situation are introduced in Section 2.1.3. Although the show cases possess the complexities, they are simplified from the real world situation. In particular the size of the problem is reduced. Repeated from Section 2.1.3, the measure of size complexity is given by:

$$Cx_{size} = M^0 C^0 \ln \|idv + ddv + dr + mg\|, \tag{3.42}$$

where idv are the variables controllable by the designer, ddv the variables not directly controlled by the designer, dr relations and constraints that dictate the association between other design variables and mg variables that determine how well the current design configuration meets the design goals. In addition to this M^0, C^0 are the number of primitive modules and number of relationships in a certain representation. The size measure complexity is calculated for the MagLev show case, BWB show case and the Coandă show case.

MagLev The designer can determine the thrust setting and the trajectory requirements of the MagLev system, the design problem appears very limited as a consequence. However, the dependent relations are much larger, due to the 5 airlines operating on 5 routes, satisfying passenger demand. Each of the 12 airline/route combinations is described by 3 parameters. Each of the 5 routes route is described by its saturation demand, satisfied demand, flight frequency, noise and CO2 emissions (25 parameters in total). Each of the 5 airlines is described by its overall profit, satisfied passenger demand and allocated slots (15 parameters in total). The passengers are described by their utility function using 2 weight factors. The airport is described by its passengers satisfied, total noise, and total CO2 emissions (3 parameters). Finally the community is described by its tolerated noise

Table 3.2: Size complexity of the show cases.

	idv	ddv	dr	mg	M^0	C^0	Cx_{size}
MagLev	2	82	1	8	8	21	761
BWB	87	114	181	1	5	13	386
Coandă	5	3	1	1	1	1	2

levels (1 parameter). The design is required by one constraint, the minimum climb angle and each of the stakeholders has a single measure of goodness, resulting in $mr = 8$. Since each stakeholder is represented by an agent $M^0 = 8$ and for the implemented structure the couplings between all stakeholders total 21. The size complexity of the problem consequently becomes 761.

BWB The BWB is described in 87 design variables, who have 114 interactions. The number of constraints, including the side constraints equals 181 and only a single objective function is used. The problem is decomposed into 5 modules with 13 interactions. This results in a size complexity of 386.

Coandă The Coandă show case has 5 design variables, 3 design dependent variables one constraint and one performance indicator. The show case focusses on a single disciplinary model with one interaction with reality. As a consequence the size complexity equals 2.

Overview The size complexity results are shown in Table 3.2. The size complexity decreases with the show cases system level. Note that the MagLev case uses a highly simplified design problem to address the (simplified) multi-stakeholder problem. The much more realistic design problem of the BWB is not considered in this realistic environment, hence the lower M^0, C^0 values. The Coandă show case is even more zoomed in to illustrate the complexities at the model level. For a real design problem to be treated with a single tool, the size complexity would be much higher since the complexities at all levels are combined and inhibit finding a solution.

Chapter 4. Dominant stakeholders in aviation: E,B,S complexity

> *"Knowledge is of no value unless you put it into practice."*
> Anton Chekov.

The previous chapter proposed the agent based modelling and simulation (ABMS) approach to study and simulate the interaction of technology and stakeholders, in order to predict the environmental impact at aviation level[87, 130]. To facilitate this approach this chapter introduces the elements and their interactions in aviation. This addresses the **E**valuative **B**ehavioural and **S**tructural complexity at the system-of-systems level (see Section 2.1). Aviation, and consequently the novel technologies, operations and methodologies, is primarily intended to transport passengers and goods between origins and destinations. Each new or novel technology should therefore "better" facilitate this transport, where "better" still remains to be determined. Even though the markets of passengers and freight (goods) vary significantly in their characteristics[47], the current evaluation is limited to the commercial passenger market since this has been more widely documented.

To investigate what constitutes a "better" technology, the *utility* of the technology for each of the stakeholders, should be determined. Section 3.1 identified that the utility derived from an aircraft technology is largely influenced by the passenger utility. This dependence makes an integrated approach mandatory. Integrated in this context is the simultaneous treatment of passenger and airline behaviour when considering the introduction of a novel technology. The interaction among stakeholders, is assumed to be captured in a quantitative internal model, providing a limited but useable implementation representing the qualitative and abstract stakeholder needs[38]. In order to model these interactions the information on the dyadic interactions between stakeholders is used. in addition to this, the proposed ABMS framework integrates this information and knowledge and disseminates the dyadic information through the system-of-systems. In particular the network structure of the framework facilitates dispersion of local interaction information and its effects through the system–of–systems. The main focus will therefore be on the identification, analysis and quantification of the dyadic ties in aviation.

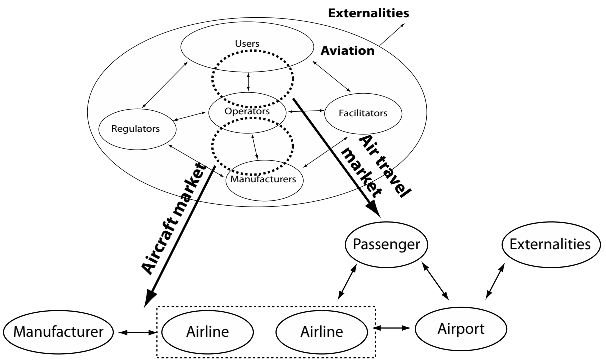


Figure 4.1: Schematic and subjective grouping of stakeholders in aviation and their decomposition in the two interactions considered.

The goal oriented behaviour is used to formulate internal models for each of the stakeholders in two markets: 1) the aircraft market, where decisions on incorporating the technology into operation are made, and 2) the air travel market, where the technology will reside its operational life. Finally, a few remarks on the implementation and interpretation of the model results are made. Finally, the qualitative QFD extension proposed in Section 2.2 is used to visualize the stakeholder interactions considered.

4.1 Decomposition of aviation

A schematic overview of the aviation stakeholders identified in the introduction and their interactions is shown in the upper part of Figure 4.1. In contrast to Figure 1.4, aviation is considered as an isolated system-of-systems, mandating explicit modelling of the externalities. The shown aggregation level is however too abstract to allow for a the quantitative agent-based approach, since the behaviour of the elements in the groups of stakeholders — users, operators, manufacturers, facilitators and regulators — is too diverse to be captured into one agent per group. A proposed further decomposition into two important interactions in aviation is shown in the lower part of Figure 4.1: the *aircraft market* and the *air travel market*. Consequently, the ABMS based on this set of stakeholders provides a limited view from the actual aviation system. Nevertheless, it provides a useful basis and indication for the application of the framework.

The stakeholders will be discussed in the following sections according to the market they affect. Since the airline is present in both markets, this stakeholder provides the connecting element between the considered markets. In addition to this, the airline is considered to have the largest influence on the decision for the implementation of novel technologies and their consequent influence on the externalities of the aviation system-of-systems. These externalities to the activities of the stakeholders in aviation are shown as a total impact on the environment external to aviation in the total system. Although many stakeholders are affected, the considerations are limited to a local community near the airport in this treatment. Even further decomposition into the various types of passengers[47], airlines, and airports[48], up to the level of individual passengers or employees is theoretically possible. Depending on the purpose of the investigation this might be desirable, but for the illustration of technology impact evaluation the decomposition level as depicted in the lower part of Figure 4.1 is considered acceptable for illustrative purposes. This simplification limited the number of stakeholders and interactions to 5 types. This nevertheless poses a challenge as will be illustrated in the following sections.

4.2 Aircraft market

The aircraft market has evolved from a technology driven market, i.e. “higher, farther, faster", to a commercial driven market[112, 183], i.e. “leaner, meaner, greener”. This has shifted the design focus from technical challenges to affordability and efficiency. These aircraft market changes originate from changes in the air travel market as well as advances in technology. The largely government owned flag carriers have transformed into a consolidated set of commercial scheduled airlines forming alliances, amended by low cost carriers and charters. This competitive environment requires airlines to operate efficiently. The required transport efficiency to accommodate the increase in air traffic has resulted in specialized companies providing aircraft services and maintenance. The large number of stakeholders and their respective equipment puts requirements on the aircraft system. The aircraft has to match the supporting equipment and infrastructure already in place. Furthermore, the efficiency requirement requires the aircraft to accommodate the predicted demand effectively and efficiently. Airlines generally operate more than one aircraft and often even more than one type of aircraft, i.e. a fleet of aircraft. Consequently, not only a match with other stakeholder equipment, e.g. airports, and infrastructure but also own equipment, e.g. existing fleet, is required. The high cost of new aircraft result in the involvement of lease companies, banks and airlines for the acquisition of new aircraft. The acquisition of a new aircraft is consequently not merely the exchange of money and product, but might involve a financial and service product as well. To generate profit, lease companies lease their aircraft to airlines and banks also get their return on investment from the airlines. Therefore, the decision for acquisition of a new aircraft is assumed to be mainly based on requirements by the airline. As a consequence, the evaluation is simplified and limited to the airline-aircraft manufacturer interaction, despite the large number of other stakeholders involved.

The relation between the airline and manufacturer is considered in more detail, as shown in Figure 4.2. Airlines base their requirements for a new aircraft on the use of the aircraft. New aircraft can be required for a new additional route in the airline network or to replace an existing aircraft. The airline can choose between a new aircraft as well as a second hand aircraft[18]. If the aircraft is intended as a replacement, the old aircraft can be permanently retired, sold or converted to a freighter aircraft. The current focus will be on the acquisition of a new aircraft intended as either providing a service on a new additional route or as a replacement on an existing route. The direct transaction is denoted by the solid arrows. The requirements imposed on a new aircraft are shown by the dashed arrow. The manufacturer considerations with respect to an aircraft programme are discussed first. Second the importance of the requirements of the airline is elaborated.

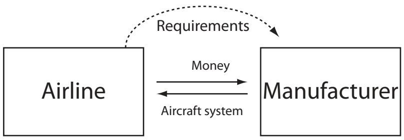


Figure 4.2: Limited view on the aircraft market stakeholders.

4.2.1 Aircraft manufacturer

Commercial aircraft design — 100+ seat aircraft — is characterized by considerable investments, financial risk and development times in the order of five to fifteen years. The investment costs can amount to a considerable fraction of the yearly revenue of the company. The financial risk is primarily caused by the large number of aircraft that have to be sold for the project to become profitable. The long development times, from initial concept to market[33], require novel aircraft to be designed incorporating future aircraft requirements. The possible changes in requirements are of considerable interest due to the aircraft lifetime, which generally spans several decades, with limited possibilities for updates (certification issues). As a consequence, the success of any new aircraft project is determined by the matching of these future requirements, which might not even exist today. Furthermore, a novel aircraft programme timescale (30+ years, the complete life-cycle of the project) can be completely different from the fleet management perspective (1-5 years, the planning perspective of an airline). Consequently, a discrepancy in planning horizon exists between manufacturers and airlines. Where the former should address issues, i.e. stakeholder requirements, much further into the future than the latter, and consequently is exposed to more risk. Besides this risk, the new aircraft might be in direct competition with an aircraft already in their portfolio, measured by for instance payload and range capabilities.

Airbus and Boeing appear to forecast and classify future needs on air travel on the amount and type of aircraft sold in previous years. Even though the forecast is no guarantee for future events and encompasses known and unknown unknowns, it can be used to estimate the economic value of the aircraft development programme. Markish and Willcox[109] and Peoples and Willcox[142] use dynamic programming to evaluate the net present value (NPV) and corresponding optimal decision strategy for an aircraft programme subject to demand changes. In line with these reference the NPV is used to define the economic value over the project life time by

$$\text{NPV} = \sum_{t=0}^{T} \frac{\pi_t}{(1+r_d)^t}, \tag{4.1}$$

where t is the time period, e.g. year, under consideration, T the project duration, r_d discount rate and π_t the profit function in time period t. The profit function π_t of the manufacturing of aircraft is determined by the costs as well as the demand and price. Both are influenced by the project itself, i.e. the aircraft design, as well as decisions made in the course of the project. The focus will be on the aircraft design, where it is assumed that the manufacturer chooses the programme with the largest expected NPV in accordance to the value engineering approach.

Programme costs The cost structure of the project is determined by three components 1) non–recurring costs, 2) recurring costs and 3) operations and support costs. The non–recurring cost are made during the design and investment on production materials. The operations and support costs are periodic costs, but largely independent of the number of units produced. Finally, the recurring costs are subject to learning curve effects. With increasing production quantities manufacturing costs per unit decrease. This decrease is either caused by increases in workers' skill level, improved production methods and/or improved production planning. This effect can be represented by a learning curve, typically expressed as a power function[7, 111]

$$a_x = a_1 x^b, \tag{4.2}$$

where a_1 and a_x are the hours required to produce the first and xth aircraft respectively, x is the cumulative number of aircraft produced and b is the parameter measuring the rate labour hours are reduced as cumulative output increases. General values for aviation, which still heavily relies on craftsmanship, are in the order of 80 to 90% reduction for each doubling of produced aircraft, hence $b \in [-0.32, -0.15]$. Low yearly production volumes on the other hand might result in organizational forgetting, i.e. increasing unit costs.

Programme value The second component of the net present value, demand and price are largely influenced by the airlines. The quality of the aircraft, attribute values, is largely constant during its lifetime. Although perceived value can change drastically by for instance incidents. The price can largely be set by the manufacturer, whereas demand is determined by the value of the product and is out of control of the manufacturer. This analysis shows the dependence of the manufacturer benefit on the airline demand, although it neglects the presence of existing aircraft and response of stakeholders (e.g. passengers, competitors and airports). To account for this interaction, Klepper[93], Benkard[18] and Irwin and Pavcnik[81] employ dynamic programming and game theory to investigate pricing and entry of aircraft manufacturers in the oligopoly environment of aircraft sales. This encompasses the dynamic environment of quantity based competition and includes the competitor strategies, resulting in a more realistic representation of the behaviour of aircraft manufacturers in a competitive environment. Examples include below marginal cost pricing to benefit from the learning curve effects and prevent organizational forgetting[18]. The description of the aircraft; random choice or 3 parameters, was however too limited to be useful for aircraft design. However, these studies show that the novel technologies are not immediately adopted overall, even if they represent increased value.

Concluding remarks As indicated in Section 2.3, this NPV is too limited to account for sustainable design. However, it provides a means of evaluating the desirability of a programme from the point of view of the manufacturer. The behaviour of the Manufacturer in several conditions is detailed in Appendix C. Furthermore, the effect of the distribution of the technology through the network of various competing airlines is investigated in Appendix D. Note that addressing the complexity at the system level, involved in designing such an aircraft, will be discussed in Chapter 6.

Table 4.1: Possible airline assets connection, ⊚, implying a weak connection, ●, implying a strong connection.

Service attributes	**Airline assets**			
	Network	Fleet	Brand	Staff
Price	⊚	⊚	⊚	⊚
Schedule	●	⊚		
Comfort		●	⊚	
Convenience	●			
Image		⊚	●	

4.2.2 Airline

Airlines provide their travel product and service based on their strategy and objective, using their assets, *network*, *fleet*, *brand* and *staff*[33]. All four items are used to create the service attributes as defined by Doganis[47]. These will be considered in more detail in the next section on the air travel market. For this section it is sufficient to identify the connection between the airline assets and the service they provide. A possible coupling for a scheduled airline is shown in Table 4.1. The ticket *price* is set based on (expected) demand for that product and changes accordingly to maximize profit. This demand is influenced by the overall service provided, requiring all assets, although no direct link exists between the two. The *schedule* provided is highly influenced by the network, hub-and-spoke or point-to-point, operated by the airline. Hub-and-spoke networks require closer matching of arrivals and departures to provide for connecting flights. Furthermore, the fleet operated is considered to limit the possibilities in schedule, either due to limits on destinations or limits on frequency, e.g. number of aircraft on a route and turn-around time. *Comfort* in flight is determined by the specific aircraft configuration, e.g. modern wide-body aircraft are often perceived as more spacious and comfortable. The comfort of the service is not limited to the air travel component, but also to the provision of airport suites and check-in ease which are part of the airline brand. *Convenience* is considered to be the matching of travel preference to actually available travel options. Consequently, convenience is determined by the network operated by the airline, e.g. number of transfers from a desired origin to a desired destination requires the (direct or indirect) operation of the airline on that route. Finally, the *image* of the airline, is determined by the brand, more concrete, the passenger expectations are different when buying a ticket from a scheduled airline and from a low cost carrier. Furthermore, the fleet, specifically the aircraft age and safety considerations, determine the image of the service. The close coupling between the assets and the service provided. This supports the argument that, in order to understand the airline aircraft value function and subsequent requirements, the service provided by them should be understood.

Since, fleet management is considered closely related to the aircraft acquisition this is considered in more depth, while accounting for the impact of the management of the other assets. Fleet planning, and the resulting *fleet plan*, is the process by which an airline acquires and manages appropriate aircraft capacity in order to serve anticipated markets

Table 4.2: Interaction between attributes of the flight plan and attributes of the aircraft, adapted from Clark[33].

	Aircraft					
Fleet plan	Capacity	Performance	Economics	Flexibility	Delivery timetable	Commonality
Adaptability	●	●	●			
Flexibility	●	●		●	●	●
Continuity						●

over a variety of defined periods of time with a view to maximizing corporate wealth[33]. The fleet plan should adhere to three criteria[33], 1) suitability on the network, 2) flexibility and 3) continuity. The demand for and valuation of aircraft is therefore translated into 1) suitability for the intended route, 2) flexibility in its deployment on possible alternative routes and under changing demand and 3) continuity of the airline fleet to reduce transition cost, like flight crew training, maintenance and spare part inventory size, besides possible political and strategic criteria[127].

Focussing on the fleet derived properties, the suitability on the intended route or route structure criterion appears rather straight forward, how cost effective can the aircraft fulfil the predicted demand on a new route or on a route where an aircraft is being replaced. This criterion is determined by payload capability, operational capacity, operational efficiency, appeal, performance and economics. The flexibility requirement is derived from the fact that aircraft might be in the fleet longer than the route structure served at the moment of acquisition. Furthermore, the aircraft might be intended for flights on multiple routes. Aircraft purchases generally take a long time from initial consideration to actual aircraft delivery. This criterion is therefore determined by the payload, operational and delivery versatility of the aircraft, specifically tailoring the aircraft to the airline needs up to the last moment before delivery. Finally, the continuity criterion is determined by the fleet operated by the airline, i.e. the coherence of the fleet, in terms of learning curve effects, customization, spares and training. The previous discussion is summarized in Table 4.2. Depending on the actual strategy of the airline, e.g. scheduled, low cost or charter airline, alternative interpretations and connections exist.

A complementary view on the purchase decision is based on Szodruch and Hilburg[180]. An extensive investigation among scheduled airlines about the relative importance of aircraft requirements by Szodruch and Hilburg resulted in the identification and classification of “key buying factors” for aircraft. The attributes identified in this study, among European airlines, are ranked on an ordinal scale from high to low importance. In comparing the attributes identified by Clark[33] and Szodruch and Hilburg[180], shown in Table 4.3, no equivalent measure was found for the delivery time table. This could either mean that aircraft currently on the market vary little in delivery times, or airlines have adapted

Table 4.3: Correlation among the attributes employed by Clark[33] and Szodruch and Hilbig[180].

	High importance										*Low importance*
	Direct Operating Cost	Aircraft price	Technical performance	Commonality	Easy maintenance	Operational flexibility	Comfort	Stability of value	External noise	Emissions	Design of cargo hold
Capacity							●				●
Performance			●		●	●		●	●	●	
Economics	●	●			●			●			
Flexibility						●					●
Delivery timetable											
Commonality				●							

their aircraft acquiring strategies to minimize the dependence or account for the generally long delivery times in relation to the cyclic behaviour of aviation[33, 47][1]. Additionally, requirements can be changed from initial purchase up to some months before delivery, e.g. moving up or down in capacity by the family concept[33]. Furthermore, the dominant key buying factors are economic in nature, i.e. direct operating costs (DOC) and aircraft price, whereas environmental considerations appear to have little influence, although still on the scale. Even though the survey was performed in 1998, when public awareness of environmental considerations was limited, the measures taken by airlines to reduce cost, e.g. weight reductions and increased rate of fleet renewal, in 2008 show the continuing importance of costs. It is therefore assumed that the criteria previously mentioned can mostly be attributed to, current or future, costs or revenue potential. Even the environmental issues should be treated in this respect. Environmental legislation is becoming increasingly strict, seen by the assembly resolutions on noise and emissions published by the ICAO Committee on Aviation Environmental Protection (CAEP)[139, 140]. This trend of increasingly strict environmental regulations is expected to continue in the future. Therefore, to have any revenue generating potential from the aircraft in the fleet, aircraft have to comply with legislation. Aircraft should therefore at least meet these (future) requirements and the larger the margin the more likely they comply with future legislations — without compromising economical and technological requirements.

Costs One method of decomposing costs, often employed in aviation is considering non-operating and operating costs, where the latter can be further divided into direct and indirect operating costs. This is shown schematically in Figure 4.3, where — subjectively — elements which are most affected by the specific aircraft are marked.

The station and ground handling, airport and ATS charges are generally levied on the basis of the maximum take-off weight. Increasing or decreasing this weight consequently directly affects this cost. Furthermore, crew costs, either cabin or flight, are based on an aircraft

---

[1] Airlines tend to buy aircraft on the economic down-cycle, to start receiving deliveries at the upturn.

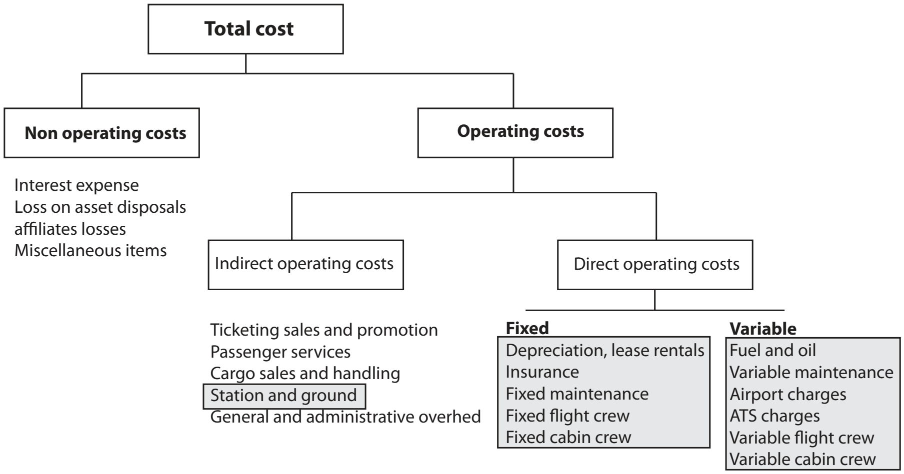


Figure 4.3: Cost breakdown of an airline, with aircraft choice influenced areas marked, adapted from Holloway[77].

size basis, i.e. more passengers means more cabin crew for a given service level. This also applies for the flight crew, as pilots of larger aircraft are generally being paid more. Depreciation, lease rentals and insurance are related to the purchase price of the aircraft, which goes up with size. Finally fuel, oil and maintenance are considered to depend on the efficiency and reliability of the aircraft respectively. However the larger the aircraft, the larger the costs. Furthermore, the efficiency generally also increases with size, resulting in a lower per passenger cost for larger aircraft. In conclusion with size the cost go up for increasing aircraft size, however this increase is generally not proportional to this size. The replacement of an existing aircraft, by a different one, is therefore considered to affect these areas directly and consequently drive the value function of the airline regarding the aircraft.

Since airlines operate a fleet of aircraft, the costs for facilities for crew training and maintenance are influenced by the choice of aircraft. Flight crew training is on an aircraft specific basis. Aircraft commonality, or family, reduces the training required for pilot certification on a different aircraft type in the same family. Maintenance training and spare part storage is subject to the same principle. The inventory required on a per aircraft basis can be lower with increasing number of aircraft of the same type in the fleet. In general, the costs for the facilities are distributed over the number of aircraft supported by them. Increasing the number of aircraft of a “family” reduces the costs per aircraft. The number of aircraft already in the fleet consequently positively affects the value of the new aircraft.

Revenue potential Besides costs, which can largely be controlled by the airline, the revenue earning potential, i.e. the possibility of earning revenue for the given costs, are equally important as indicated in Equation 4.9[33]. An increase in aircraft size, has direct impact on the potential satisfied demand. However, increasing the capacity does not automatically result in increased revenue as it still has to be filled. With respect to revenue potential, the size, or number of seats of the aircraft and the payload mass determine the amount of revenue generating potential of the aircraft per flight. The range, more precisely the payload range diagram, determines the distance[2] over which the payload can be transported for a desired payload per flight. The number of flights which can be performed is determined by the aircraft speed, a higher speed means larger productivity and increased revenue per time period.

Utility function Combining all the complex airline behaviour in a single mathematical relation can only be performed if many considerations are neglected. Nevertheless, to illustrate the ABMS approach this single relation representation is sufficient. More detailed behavioural models are possible but require a more sophisticated behavioural model. A novel aircraft, with different cost and revenue characteristics has an effect on the airline profit function, Equation 4.9. The costs (per flight) are directly affected by the novel aircraft, the direct operating costs might drop and the purchase price effect on the indirect operating costs is also directly measurable. On the other hand, the effect on the revenue function is much less direct. The capacity, constraint on an existing route, might be increased, but unless this additional capacity is filled with additional passengers, the revenue is not affected. This shows that the control of airlines over their costs is larger than over their revenue, indicating the difficulty of managing airlines[47]. The general utility function used is of the form

$$U_A = \boldsymbol{\beta} g(\boldsymbol{x}) - \alpha p + \xi, \tag{4.3}$$

where U_A is the value attributed to the aircraft considered (measurable) attributes x, purchase price p and unconsidered attributes ξ. The weight factors $\boldsymbol{\beta}, \alpha$ are set by the airline, and relate the aircraft attributes/properties to the fleet suitability, flexibility and continuity, and are influenced by its environment. Fitting the previous considerations in a value function, the properties identified could be related to the payload capability P_c, e.g. number of seats, volume or weight, range R, cruise velocity V_{cr}, and purchase price p[142],

$$U_A = \beta_1 P_c + \beta_2 R(P_c) + \beta_3 V_{cr} - \alpha p + \xi \tag{4.4}$$

The coefficients are determined by the effect of these parameters on the airline cost as well as the revenue expected from the network structure used. Other elements which might also affect the value are determined by the take-off performance requirements. For instance if the aircraft is to be used on a particularly short runway, this might limit the choices. The unconsidered parameters of choice — included in the “quality” factor ξ — might encompass the political and strategic, unmeasurable preferences expressed by the airline. Furthermore, items such as financing and technical and operational support compose a significant part of the considerations, hence only looking at the aircraft might provide a too narrow view, consequently the aircraft product should be designed according to the life cycle analysis to incorporate these additional values and stakeholders. For the illustration of the ABMS in Appendix C these attributes are captured in a single aircraft specific utility and the manufacturer can only set the price.

---

[2] This distance depends on the average wind speed and direction encountered en route.

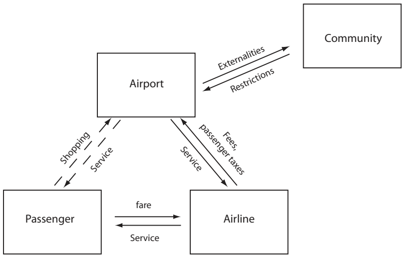


Figure 4.4: Limited view on the travel market stakeholders.

4.3 Air travel market

The air travel market has seen considerable changes in its history. It started as an elite means of transportation, evolved into a mass transportation system, due to technological developments, and might evolve even further to support future stakeholder needs. This continuous change, due to for instance effect of internet on the booking process, and the increasing pressure for a sustainable aviation, results in a dynamic system of systems where technology valuation is subject to continuous change. As a consequence, technology impact evaluation needs to incorporate this continuous change.

The demand for air transport is derived demand. Initially, the passenger requires or wants to be somewhere at a certain time to perform a certain activity[16, 24] and requires transport to be able to physically participate. Consequently, the travel product is a means of transport and the value is mainly determined by the activity at the destination. Since the service provided is directly experienced by the traveller, a differentiation in quality, or level of service (LOS)[179, pp.406], remains possible[77]. This direct experience of passengers with aviation initiates competition based on product differentiation on LOS. This LOS consists of many components, ranging from booking process to the actual travel and after-sales services. Due to the integrated nature of the air travel market, the LOS observed by the customer is also a function of other trip characteristics, not directly influenceable by an airline. Examples are accessibility of the origin and destination airport and service of the travel agent[179, pp.406]. The travel product experienced by the passenger is therefore an interplay of many stakeholders and their services. Unfortunately, providing this service also introduces externalities. In this case only the community residing near the airports is considered. For clarity, the considerations are limited to the services provided by the three stakeholders depicted in Figure 4.4, consequently the four stakeholders considered here is not a limitation of the ABMS.

4.3.1 Passenger

The traveller or passenger is the stakeholder deciding for an air travel product. As argued in the previous section, this decision is based on the purpose of the trip and the level of service, including the ticket pricing. As a start the decision process is modelled for a single passenger to introduce the concepts of discrete choice analysis and subsequently extended for group decisions.

Single passenger Translating the LOS into a single decision rule neglects a lot of the nuances incorporated in the decision making process of the traveller. For the illustration of the ABMS this complex process is reduced to one goal of the traveller: the satisfaction derived from a travel product is seen as a minimization of inconveniences with respect to the intended purpose of travel,

$$U_{p,i} = U_{d,i} - \alpha_i F_p + \boldsymbol{\beta}_i g(\mathbf{x}_p) + \xi_i \tag{4.5}$$

where U_p and U_d are the value derived from product p and destination d for traveller i, diminished by the fare F and other measurable and considered[3] service attributes $\boldsymbol{x}$, and ξ captures the unmeasurable and unconsidered elements. The scalar α_i and vector $\boldsymbol{\beta}_i$ are the valuations allocated to each of the product attributes by traveler i. Many factors, like trip time/ travel time, fare, and service level affect the decision for a certain service[17, 179]. Furthermore, Doganis[47, pp.237] identifies five key product attribute groups; price, schedule-based, comfort based, convenience and image. Where the value $V_{d,i}$ is determined by external factors, e.g. economic growth and holiday season. The resulting product value, $V_{p,i}$ is assumed to determine the product choice.

In making a choice for a travel product (return trip), the traveler is assumed to perform a sequence of two evaluations: 1) determine whether the value for traveling by air is larger than alternative — available — modes of transportation. Examples of alternative modes are train and car, but also no travel, enabled by for instance e-conferences. 2) Within this chosen nest of transportation mode the product with the maximum perceived value[193]. An alternative interpretation is that the products sharing modes of transportation also share characteristics and can consequently be grouped into nests. Furthermore, the valuation the products in the nest is assumed to influence the nest value to a certain extent.

Various discrete choice models have been developed to determine the probability that a customer chooses a certain product, depending on the characteristics of the choice procedure and the distribution of the unconsidered elements of the choice, ξ. Multinomial models consider three or more alternatives — in contrast to binomial models. Furthermore, the choice for a mode of transportation and subsequent choice for a specific travel product is considered to comply with the nested approach described by Akiva and Lerman[17] and detailed in Appendix A,

$$\mathcal{P}(p) = \mathcal{P}(C_n)\mathcal{P}(p \in C_n) = \frac{e^{\mu U'_n}}{\sum_n e^{\mu U'_n}} \frac{e^{\sigma U_p}}{\sum_{p \in n} e^{\sigma U_p}}. \tag{4.6}$$

The nested multinomial logit model combines the choice for a nest $\mathcal{P}(C_n)$ and the choice for the product within the nest $\mathcal{P}(p \in C_n)$ into a probability for selecting product p by the passenger i. The σ and μ terms describe the extent of the individual product value influence on the nest value.

Multiple passengers The fact that the group behaviour can be captured in a single distribution is the result of emergent behaviour among passengers. Due to this emergence, the decisions of multiple passengers can be represented by a single nested-logit model, i.e. aggregation. Note that the ABMS framework allows for a relaxation of this simplification. The aggregate group decision function is given by considering the overall demand

---

[3] Considered means considered by the researcher, in contrast to considered by the passenger.

and distributing it according to the group preferences;

$$Q_p = Q_m \frac{\left(\sum_{p=1}^{P} e^{U_p}\right)^{\theta}}{e^{U_0} + \left(\sum_{p=1}^{P} e^{U_p}\right)^{\theta}} \frac{e^{U_p}}{\sum_p e^{U_p}} \tag{4.7}$$

where Q_P is the demand for a product category P, e.g. air travel, Q_m is the saturation demand for the market, and U_0 the value perceived for not choosing any of the available air travel products $p \in [1, P]$ and θ determines the correlation among alternatives within the air transport mode nest and the effect of product value within the nest on the nest value. A value of $\theta = 0$ corresponds to nest–choice airline–attribute indifference, and $\theta = 1$ to the un-nested model[193][4]. The saturation demand Q_m for a route is dependent on the attractiveness of the origin and the destination, which might change over the year and can be considered dependent on $U_{d,i}$, as well as the income and population size at the origin.

Assuming one distribution for all passenger types, e.g. business, visiting friends and relatives (VFR), or leisure[47], is a rather crude method. Further subdivision or segmentation into categories per route can be employed, to implement the various attribute valuations. The saturation demand Q_m and attribute valuation U_p and θ consequently have to be replaced by their, per passenger type, counterparts. The level of detail achievable is limited by the data on the passengers available. For illustrative purposes the single passenger type representation is used.

4.3.2 Airline

Airlines face the challenge of allocating rigid capacity, consisting of number of aircraft, aircraft capacity and frequency of operation, to the flexible demand. Specific for the air travel is the non-storable capacity, i.e. airlines cannot store generated capacity not filled by demand once the aircraft is in the air, furthermore, demand is also not storable. Furthermore, once an aircraft is scheduled to leave, the marginal costs are low, prompting the airlines to sell last minute seats slightly above or at the marginal costs. This conflicts with the fact that the passengers willing to pay more for their seat (generally business travellers) book their flight relatively short in advance (generally one or two days before). Furthermore, the various passenger preference groups identified in the previous section, e.g. business and holiday travellers, have their own preferences. Consequently airlines segment their products — basically seats — on the attributes identified by Doganis[47], specifically for the passenger groups expected. All considerations combined result in complex revenue and seat management procedures[16]. Graphically this can be illustrated by filling the demand curve as much as possible, as shown in Figure 4.5. In order to maximize the profit and capture market share, an airline thus provides differentiated services on its route network, specific to each passenger type. Fences should prevent high revenue passengers from deviating to lower fare products[16, 47], i.e. passenger slippage. And demand predicting considerations maintain enough vacant seats for the expected high revenue last minute travellers[16]. These considerations are simplified and captured in a single equation, emulating the airline behaviour. More elaborate models are feasible, however they require

---

[4] On a side note, for values $0 < \theta < 1$, the additional value for a product in the nest increases the nest's probability, hence this can be seen as a positive externality.

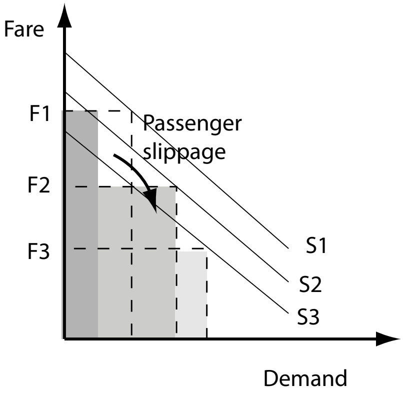


Figure 4.5: Demand curve for various products offered on one aircraft trip.

more computational effort and divert the attention from the integrated treatment proposed by ABMS.

The market share on a single route of a service is determined by the value of the product in relation to other products. In a duopoly, where each airline only offers one service, the relative market shares are given as[193]

$$\ln \frac{S_1}{S_2} = \boldsymbol{\beta} \left(g(\boldsymbol{x}_1) - g(\boldsymbol{x}_2) \right) - \alpha \left(F_1 - F_2 \right) + \xi_1 - \xi_2 \tag{4.8}$$

Market shares for more than two competitors have been detailed in Appendix A. In order to achieve the goal of maximized profit[29], the airline tries to match capacity as closely to (predicted) demand as possible[47, 77]. A more general approach would be to assume that airline a tries to maximize profit π_a for its product portfolio P_a

$$\pi_a = \sum_{P_a} F_{p,a} q_{p,a} - c(q_{p,a}, \boldsymbol{x}) - C_a \tag{4.9}$$

where the profit π_a of the airline is determined by the revenue generated by all its services, minus the cost c for specific services and the overall costs C_a. Since most costs are on a per passenger basis (e.g. ticket services, on-board meals) or on a per flight basis (e.g. fuel, pilot salaries, runway charges) this is also represented in the cost function . Furthermore, since the marginal cost for an additional passenger are considered to be low, once the aircraft is scheduled to leave, they are neglected and only a per flight, per route r cost basis is employed,

$$\pi_a = \sum_{p} \sum_{r} F_{r,p,a} q_{r,p,a} - c_{r,a} f_{r,a} - C_a \tag{4.10}$$

The airline costs are manageable by the airlines; on the short term by choosing the appropriate schedule, directly affecting the direct operating costs, and long term, by appropriate asset management, e.g. appropriate fleet and network. The revenue on the other hand can only be influenced due to its dependence on external factors, e.g. passengers.

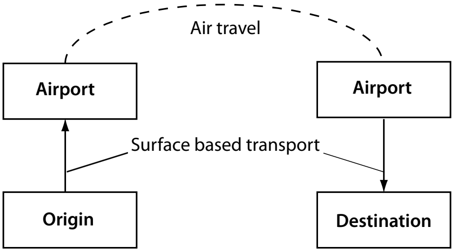


Figure 4.6: Airport as an element in the passenger transportation system[179].

4.3.3 Airport

Airports, although often in public hands, are increasingly operated and managed like commercial corporations. Hence, the airport is assumed to be a commercial company, which provides the supporting infrastructure — Land and air based services — for the services provided by airlines. Consequently the airport brings passengers and airlines together[46]. Furthermore, airports should be considered part of a larger ground based transportation system, transporting passengers from their actual origins, e.g. home, to their actual destinations, e.g. company or hotel, depicted in Figure 4.6. Large differences exist between the seamless transport approach taken in Europe and the lack thereof in the United States. The capacity of passengers of these modes and the capacity of the airport to facilitate passengers using these surface based transportation modes, are only two of the capacity constraints of the airport[179]. This is considered the land side of the airport, the airside of the airport consists of the facilities for receiving and handling aircraft[46]. Consequently, airport economics consist of an airline service part as well as a passenger service part. The airline services consist of, but are not limited to, air traffic service provision and runway and gate use. Airport charges are generally levied on an aircraft weight basis[46], but are changing to a more demand oriented approach. For example, charges are increased for highly desired arrival and departure times and night times or polluting aircraft. The services per passenger consist of security provisions, check-in desks and baggage handling and are usually levied as a percentage of the ticket fare. Furthermore, the airport is often organized as a commercial centre, providing among others tax-free shops and restaurants[179]. The airport services are provided by expensive, inflexible infrastructure, which is limited in capacity. The number of services is generally constraint both in number of aircraft which can be accommodated at any time in the airspace, on the runway and at the gates. That is there is a maximum number of slots N_S available to the airport, which is determined by technical, safety or environmental considerations[157]. Furthermore the number of passengers is limited by the airport or connecting transport capacity.

As an example a single runway airport is chosen. The profit function[29], which is to be maximized is composed of two parts 1) passenger related 2) airline related;

$$
\begin{aligned}
\max_x \pi_{ap} = \sum_i \sum_r r_{i,r} f_{i,r} + \sum_i \sum_r t_{i,r} D_{i,r} - C_{ap} \\
\sum_i N_i \leq N_{ap} \\
\sum_i \sum_r D_{i,r} \leq D_{ap}
\end{aligned}
\tag{4.11}
$$

where π is profit, $r_{i,r}$ the profit generated (e.g. revenue minus costs) per airline i per route r per flight, $f_{i,r}$ the number of flights for airline i on route r. The fare levied from the passengers is denoted $t_{i,r}$, and is usually a fraction of the fare plus revenue from purchases made by passengers, $D_{i,r}$ is the satisfied passenger demand and C_{ap} are the fixed costs of the airport, e.g. maintenance and wages. To emulate the constrained nature of the airport two bounds are implied, maximum number of flights N_{ap} and maximum number of passengers D_{ap}. Since, most airport revenue is generated by the passengers[46], the airport wants to maximize the number of passengers and their spending to maximize profit. This has been eloquently put by Doganis[46] as; the more noisy and crowded the airport the better. This is however contrary to the level of service provided for the passengers[178], which is negatively correlated to this crowdedness.

4.3.4 Local community

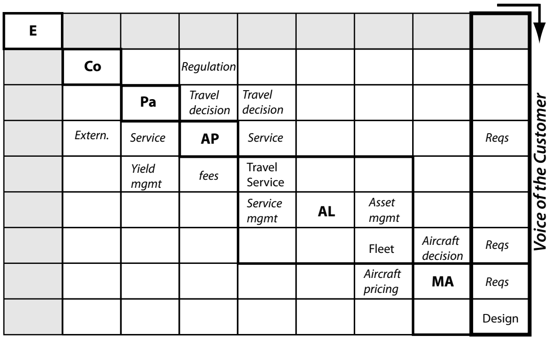
The community living in the vicinity of the airport is assumed to have an adverse taste for the noise producing activities of the airport but only if they exceed a certain threshold. The community behaviour in reaction to exceeding this threshold is related to influence exerted on the airline and airport service through governments and subsequent regulation. This influence results in additional or more strict constraints on the operations of the airport and airlines. For this inference the Kosten formula[157] is used to quantify the community behaviour

$$
B = 20 \log_{10} \left(\sum_{j=1}^{N} w_j 10^{L_{A\,\max_j}/15} \right) - 157 \tag{4.12}
$$

where the weight factor w_j is dependent on flight time, and is assumed to be 1, i.e. daytime flight, B is the total noise load in Kosten units $[Ke]$, N the total number of aircraft movements in a year, and $L_{A\,\max_j}$, the maximum A-weighted sound level for movement j at the location of interest. A Kosten level of 35 is the limiting total noise level considered acceptable by the fictitious community. Furthermore, assuming equivalent noise contours per aircraft — i.e. similar aircraft type and path — the total number of slots can be rewritten as a function of the maximum A-weighted sound-level,

$$
20 \log_{10} N_{ap} = B_{acc} + 157 - \frac{3}{4} L_{A\,\max_j} \tag{4.13}
$$

where B_{acc} is the acceptable Kosten level of 35 and N_{ap} the maximum number of movements on the airport. The fact that not only a downward pressure on the number of movements exists is based on the consideration that the community also derives positive externalities from the operation of the airport. Examples of these positive externalities are economic profit, ease of travel and connectivity[85].



E								
	Co		*Regulation*					
		Pa	*Travel decision*	*Travel decision*				
	Extern.	*Service*	**AP**	*Service*				*Reqs*
		Yield mgmt	*fees*	Travel Service				
				Service mgmt	**AL**	*Asset mgmt*		
						Fleet	*Aircraft decision*	*Reqs*
						Aircraft pricing	**MA**	*Reqs*
								Design

Figure 4.7: Reduced primary stakeholder interaction matrix.

4.4 Combination of markets

The second and third section each addressed one particular market interaction of stakeholders. The presence of the airline stakeholder in both markets indicates the mutual influence between the two. The combined picture is shown in Figure 4.7. On the diagonal the decision making entities, i.e. stakeholders, and off-diagonal their behaviours are shown. The passenger, **Pa**, is connected to both the airport, **AP**, and the travel service provided by the airline, **AL**, by his/her decision to travel. The provision of the travel products affects the community, **Co**, who affects the airport through regulations. The airline on the other hand influences this travel service with yield management, e.g. which routes are served and their frequency and fare. The airline provides the travel service using its assets; network, fleet, brand and staff. Managing the asset of interest, the fleet, requires the acquisition of new aircraft provided by a manufacturer, **Ma**. The manufacturer on the other hand sets a price for the aircraft in his portfolio. Each of these interactions and stakeholders results in requirements for the new aircraft design. Finally, **E** represents the unconsidered and/or unknown influences of the stakeholders on other stakeholders or their environment. This is added for completeness and serves as a reminder that not this inference is never complete. Nevertheless this limited inference shows the direct connection between the AL, Ma and the design, i.e. aircraft development programme. The indirect influences stem from the AP, Pa and Co, who also have an effect on the design.

With this structure in place several advantageous with respect to the non-integrated identification of requirements can be identified:

- The completeness of the interactions between considered stakeholders can easily be seen and updated. As an example, additional stakeholders, as required in the case of additional environmental costs can be incorporated in the framework
- Behaviour and interactions change continuously, the information of new behaviour or additional interactions is often based on dyadic ties. The consequence of this isolated information for the design or any of the stakeholders can be readily identified. At the very least the stakeholders influenced by the changed behaviour can be identified.

The previous considerations are mainly based on representing the continuously changing interactions. From a prioritization point of view the diagonal stakeholders could be rearranged into blocks which might have similar requirements from the product as well as organized into groups describing importance in influence on the design. In order to better facilitate this, the off-diagonal terms currently describing the behaviour need to be replaced by a house of quality (HOQ). Each of these HOQs has inputs representing the needs vertically and the corresponding solutions for this need horizontally. The resulting input, indicated by the final column of Figure 4.7 for the design HOQ represents the underlying considerations enabling and influencing the behaviour.

Chapter 5. Coupling of behaviour and technology impact: E,B,S complexity

> *"The real danger is not that computers will begin to think like men, but that men will begin to think like computers."*
> Sydney J. Harris.

Chapter 2 discussed the problems arising in environmental impact assessment at the system-of-systems level. Chapter 3 proposed a research method implement an environmental impact evaluation at the system-of-systems level. Chapter 4 applied this approach to aviation and identified the goals, strategies and behaviour of stakeholders in two markets. This chapter illustrates the difficulty of actually implementing the proposed framework and applying it to a novel technology. The complexities which are encountered at the system-of-systems level are **E**valuative **B**ehavioural and **S**tructural complexity as discussed in Section 2.1. Consequently, this chapter discusses how the behaviour identified in Chapter 4 is captured in agents within an ABMS and how it can be applied to evaluate the environmental impact. The first show case of the MagLev system will focus on emergent behaviour, and the interaction between stakeholders. This show case will address the behavioural and structural complexity at the system of systems level. In order to predict stakeholder responses to novel technologies the maturity of the design is important. The maturity of the MagLev technology used in the first show case is limited and as a consequence a second show case is used to illustrate the difficulties of predicting stakeholder behaviour. This case will focus on the alternative behaviour enabled by the Prandtl Plane concept. This show case addresses the evaluative complexity and the behavioural complexity of predicting what stakeholders want from a technology and how they will react to a novel technology in the future.

The goal of this chapter is to illustrate the difficulties encountered in the actual implementation of the tools proposed in Chapter 3. Completeness is intended in the illustration of the tools (and their limitations), not in the technology evaluation.

5.1 Effect of emerging behaviour: MagLev system

Aircraft noise and emissions have been identified as major contributors to the environmental impact of aviation near airports. One of the dominant sources of this external noise is engine noise during take-off[25, 100]. This engine is also causing a deterioration in air quality in the airport vicinity. Both noise level and emissions are mainly determined by the thrust-setting of the engine. With the introduction of the large bypass engine the jet velocities have decreased, resulting in a reduction in noise production by aircraft while at the same time lowering fuel consumption. This increasing bypass ratio strategy, although still researched, suffers from ever increasing costs, shown in the acquisition and or maintenance costs of engines[45], with decreasing returns on efficiency gain. A complementary strategy is to assist aircraft during take-off using an external force, consequently allowing lower thrust settings, possibly reducing environmental impact. This principle has been in use on runway-length-restricted military aircraft-carriers since the 1930s. The means of generating this external force vary from hydraulic and steam — aircraft carriers —, to pulleys — hang-gliders —, and Magnetic levitation concepts — NASA proposal for spacecraft launch assist[82].

The ABMS framework allows for an separate treatment of isolated technology impact and its effect on the stakeholder behaviour. This separates the system level and system-of-systems level analysis. At the system-of-systems level analysis the technology is seen as a coupled set of attribute values. The limitations of this approach will be discussed in Section 5.2 and Appendix A. The environmental impact of a Maglev system will be investigated in more detail, including the enabling features. This system level analysis is followed by the evaluation of the (changed) behaviour of the corresponding stakeholders and subsequent impact at the system- of-systems level, using the ABMS approach.

5.1.1 MagLev concept

For the MagLev system, the aircraft acceleration in take-off is provided by a cart, which is accelerated along a magnetic rail. This cart is attached to the landing gear of the aircraft as shown in Figure 5.1. With set aircraft engine thrust, both cart and aircraft are accelerated up to the desired take-off velocity, V_{TO}. This take-off velocity is higher than the normal aircraft velocity to allow for reduced in flight thrust settings. Once the desired velocity is reached, the aircraft detaches from the cart to continue on its own power. To comply with regulations, i.e. obstacle clearance, the aircraft climb trajectory should at least lie above the current trajectories. The forces and energy required from the system can be estimated when looking at aircraft taking off from current airports. The considered aircraft range from a Boeing 737-800 ($MTOW = 85100kg$) to an Airbus A380 ($MTOW = 650000kg$). The force generated by the cart at each instant of time on the aircraft is approximated by

$$F_m = (\text{MTOW} + M_c)\, a + C_D \frac{1}{2} \rho V^2 S - T \tag{5.1}$$

where the drag coefficient, C_D, is the drag of both the aircraft and the cart combination. Assuming an cart weight, M_c, negligible with respect to the aircraft and also limited influence on the aerodynamics, the equation can be simplified to

$$F_m = \text{MTOW} a + C_D \frac{1}{2} \rho V^2 S - T \tag{5.2}$$

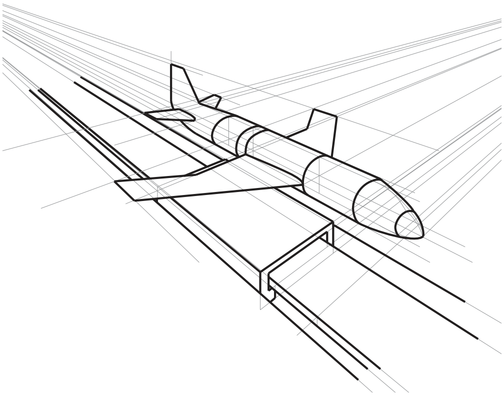


Figure 5.1: Schematic representation of the Maglev concept.

Table 5.1: Force and energy required by the MagLev system if no thrust is provided by the aircraft.

	MTOW $[kg]$	C_{D0} $[-]$	S_W $[m^2]$	$V_{\max}$ $[m/s]$	F_m $[kN]$	E_{req} $[MJ]$
B737-800	85,100	0.0212	105.4	150	447	992
B777	324,370	0.0212	427.8	150	1,712	3,793
A380	650,000	0.0212	845.0	150	3,428	7,596

the acceleration, a is limited by passenger comfort to $0.5g_0$ and assuming a drag coefficient of $C_D = 0.0212$[157] the maximum force required by the Maglev system, for zero aircraft thrust setting can be calculated. Furthermore, the energy requirement per take-off is given by,

$$E = \frac{1}{2}\text{MTOW}V_{max}^2 + \frac{1}{8a}\rho C_D S V_{max}^4 \tag{5.3}$$

The resulting maximum force and energy requirements for a launch velocity are shown in Table 5.1 and the effect of the increase in desired velocity is shown in Figure 5.2. The efficiency of the MagLev system is set to 50%[82]. Consequently, the required energy is twice the amount given by Equation 5.3. The forces accelerating the aircraft have to be transferred from the cart, through the landing gear, to the aircraft. The landing gear therefore requires strengthening, while the cart structure holding the aircraft in place should also allow safe detachment of the aircraft once the desired take-off speed is reached. Furthermore, the integration of the cart system with the remainder of the airport requires further investigation, such as cart return to the start of the runway, subsequent aircraft attachment and the required safety operations. For a real system design these issues need to be resolved.Although a lot of design issues have been left unconsidered, which add complexity to the evaluation and cost to the system, it is assumed for this treatment that the concept is feasible.

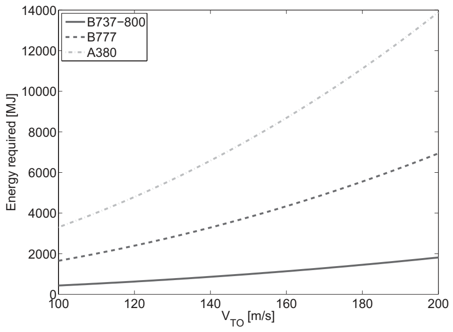


Figure 5.2: Energy requirement for various aircraft and desired take-off velocities, $a = 0.5g_0$.

5.1.2 Technology impact assessment

Focussing on a single part of the life-cycle of the proposed MagLev system, i.e. the operational life phase, simplifies the system level evaluation considerably without compromising the illustration of the tool. Note that this assumption does have a large effect on the environmental impact results of this technology. Nevertheless, the goal is to illustrate the ABMS tool and the effect of intertwined stakeholder behaviour on the (simplified) environmental impact. In addition to this, a complete analysis in the conceptual design phase is infeasible as not all characteristics are known or designed yet. During the operational life-cycle of the MagLev system the main change is the take-off procedure of the aircraft. The impact assessment is therefore focussed on this part, neglecting other implementation issues.

Single aircraft take-off

Consider a Boeing 737-800 with CFM56-7B26 engines, assume the absence of a wind vector, the simplification of the reference frame to a flat non-rotating earth and coordinated flight. Furthermore, the aircraft is considered to fly in a standard atmosphere, where the weight W remains constant during the climb. Finally, control is achieved by thrust setting Γ and flight path angle γ, for bank angle $\mu = 0$. The resulting equations of motion, for a point mass representing the aircraft, can be written as:

$$\begin{aligned} \dot{x} &= V\cos\gamma \\ \dot{y} &= 0 \\ \dot{h} &= V\sin\gamma \\ \dot{V} &= \frac{T(\Gamma)-D}{W} \end{aligned} \tag{5.4}$$

To evaluate the effect of the various thrust settings on the noise and emissions, the NADP-1[79] departure is used as a reference. This reference procedure is adapted to accommodate the MagLev system. The controls are kept constant to their initial set values, $\gamma = \gamma_0$, $\Gamma = \Gamma_0$, up to the point where the velocity or altitude, decreases below the NADP-1 reference trajectory, $V(t) \leq V_{ref}(t), h(t) \leq h_{ref}(t)$[99]. The initial thrust settings Γ_0 are varied from 0% to 100% of the maximum take-off thrust. With these thrust settings, the aircraft is accelerated along the runway to $150m/s$. This velocity, larger than the NADP-1 take-off velocity of $97m/s$, can be achieved in two ways,

1) keep the runway length constant, hence an appropriate reduction in force of the MagLev system with increasing aircraft thrust setting is required
2) keep the MagLev force constant, for increasing aircraft thrust setting the runway length becomes shorter.

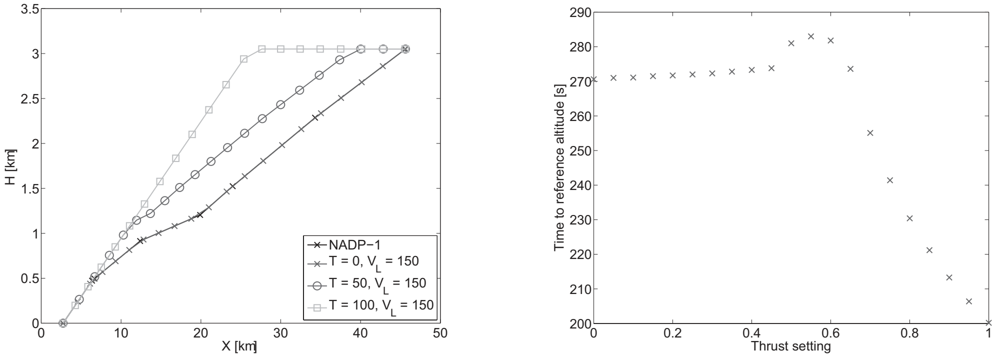
Since the allowed acceleration is limited by passenger comfort, the first option is implemented. Furthermore, due to the higher take-off velocity, the use of flaps is generally not advised. During the simulated take-off the flaps remain retracted. This affects the maximum allowable lift coefficient as well as the drag of the configuration. The trajectory is simulated up to an altitude of 3 kilometers. From this point onward, the aircraft is considered to continue its trajectory into a horizontal cruise, ending up at the same reference-point to make a fair comparison between trajectories. The altitude of three kilometers is chosen as the difference in noise from this point onward is considered negligible.

Results

The environmental impact of the MagLev system is characterized by noise and emissions. The resulting aircraft trajectory is evaluated using the integrated noise model (INM)[58] and an Emission evaluation tool[80] to determine noise contours and emissions during take-off respectively. The INM requires the aircraft three dimensional trajectory, thrust setting in time and the aircraft properties to determine the noise contours. Whereas the emission evaluation only requires the development of the thrust setting along the trajectory.

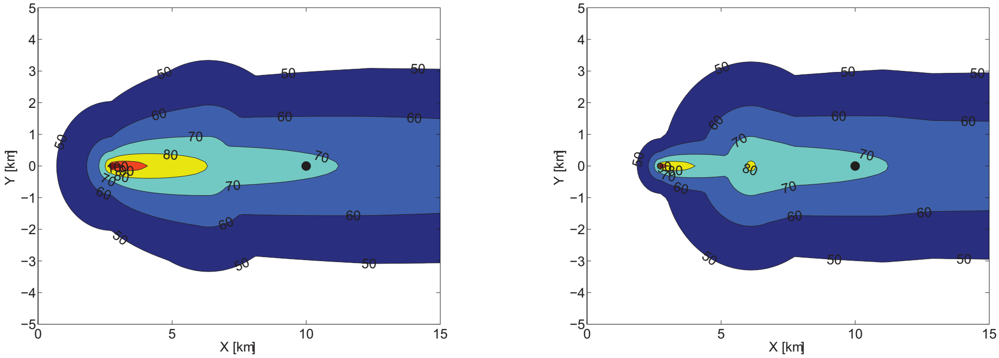
Trajectory The trajectory calculated for the various thrust settings is given in Figure 5.3a. The results show that the implemented control strategy results in a climb of $7.4\,^\circ$ up to the point where the velocity decreases below the threshold velocity, determined by a maximum lift coefficient, $C_{L_{\text{max}}} = 0.8$, in clean configuration. When this point is reached, the thrust and flight path angle are set to the NDAP-1 values corresponding to the altitude. Depending on the initial thrust settings this occurs; almost immediately — $T = 0\%$ —, during the climb — $T = 50\%$ —, or not at all — $T = 100\%$ — before reaching the target altitude of $3km$. The difference in noise and emissions with respect to the reference trajectory is therefore expected to be minimal for low initial thrust settings. For the maximum thrust setting the climb can be continued up to altitude affecting the time to reference considerably, as shown in Figure 5.3b.The influence on the noise and emissions is therefore expected to be significant for higher thrust settings. The effect of the altered trajectory on the noise contours and emissions is considered in further detail in the next two paragraphs.

Noise Figure 5.4 shows four A-weighted noise contours for the NDAP-1 and MagLev departures for three different thrust settings. For the low thrust levels ($T = 0$), the threshold velocity, is reached quickly, after which the thrust has to be increased to the values set by the NDAP-1 departure. This is apparent in the noise contour plot when comparing Figures 5.4a and 5.4b. The noise reduction due to the low thrust setting in the immediate vicinity of

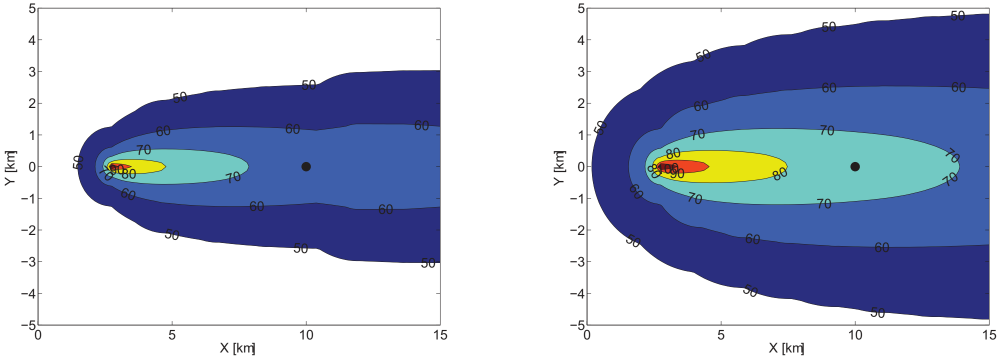


(a) Trajectory. (b) Time to reference.

Figure 5.3: Departure properties for various thrust settings.

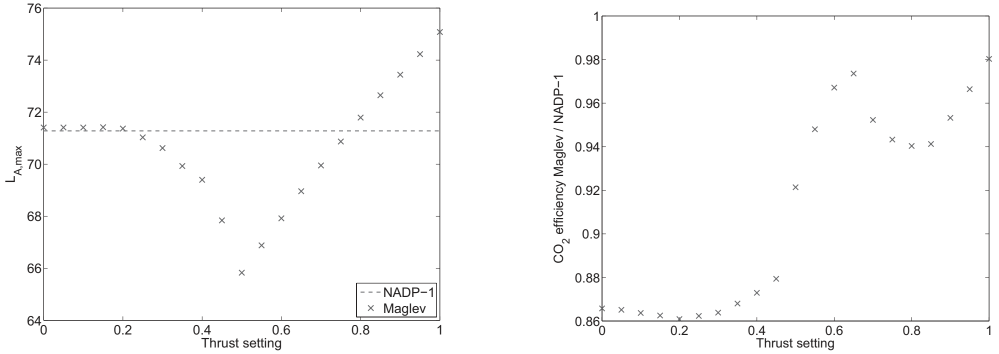


(a) NADP-1 noise contours. (b) $V_L = 150m/s, T = 0.0T_{\max}$



(c) $V_L = 150m/s, T = 0.5T_{\max}$ (d) $V_L = 150m/s, T = 1.0T_{\max}$

Figure 5.4: Noise contours and location of the test point.



(a) A-weighted maximum noise level.

(b) Carbon dioxide efficiency for take-off.

Figure 5.5: System level environmental impact reduction for different thrust settings.

the airport is significant. However, the noise level increases at $X = 6$. At this location the speed decreases below the NDAP-1 trajectory and the engines are throttled to continue on the NDAP-1 reference trajectory. When the initial thrust is increased to 50% of the take-off thrust, the noise in the airport vicinity is increased with respect to the zero thrust scenario but remains lower than the NDAP-1 departure. Furthermore, the distinct increase in noise level, when the engines are set to climb thrust is absent. Further increase of the thrust level to 100% of the take-off thrust, results in an increase of initial noise levels around the airport, negating the beneficial effects of the MagLev assisted launch for the surroundings of the airport.

For a more detailed investigation of the noise effects, a location underneath the trajectory is randomly selected ($[10, 0]$). In this location the maximum A-weighted noise level is evaluated for various thrust settings in Figure 5.5a. Due to the location of the throttling of the engine, the initial noise levels are larger than those due to the reference departure. However, with increasing initial thrust levels the location specific noise levels decrease, reaching a minimum at $T = 50\%$. After this minimum the noise levels increase due to the higher engine noise caused by the larger thrust settings. At a thrust level of about 75% the A-weighted noise level surpasses the noise level of the NADP-1 departure and continues to increase up to the maximum thrust setting.

Emissions The emissions during take-off are generally decreased with respect to the NADP-1 reference trajectory as shown in Figure 5.5b. For the low thrust settings this is caused by the reduced engine noise during the first climb segment. For the high thrust settings, the shorter time to altitude reduces emissions, as shown in Figure 5.3b. The additional energy is not for free and comes from the MagLev system, which has not been accounted for. The energy powering the maglev system can originate from several sources, nuclear and coal powerplants, solar farms, wind farms or a combination thereof. The impact of this power consumption cannot be determined without further knowledge on the actual implementation[1]. As a best case scenario with respect to emissions, the wind farm is taken as the source of power. This introduces issues of time and situation specific power

---

[1] Note that this is a clear example of how the chosen system boundary affects the environmental impact evaluation.

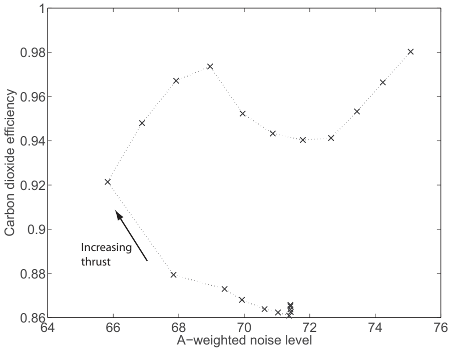


Figure 5.6: Combined effect of noise and carbon emissions of the MagLev assisted departure.

output, which contrasts with the need for constant power requirement of aircraft take-off. As a consequence, the emissions will be higher than predicted.

Impact of the MagLev system Not all thrust values considered in the previous section are considered viable. In particular the safety issues arising for the zero — and low — thrust conditions are considered too large an obstruction to be used. As an example; in case of low engine thrust settings, single engine failure is considered to result in an unrecoverable aircraft. In addition to this, similar noise reductions are achievable when using the safer higher thrust settings. For thrust settings larger than 50% and smaller than 75% the MagLev concept looks beneficial both from the noise and carbon dioxide perspective. This is solely based on the system level quality measures employed here. The actual performance of an implemented MagLev system[2] is likely to be different due to technical issues not addressed, e.g. safety, passenger acceptance and comfort. However, for illustrative purposes the current design is considered “final” for the system-of-systems evaluation.

5.1.3 System of systems level impact

The stakeholders previously identified and characterized in Chapter 4, i.e. airport, airline, passenger and local community are influenced by the MagLev system, as shown schematically in Figure 5.7. In order to determine the system-of-systems level impact of the Maglev assisted take-off system, multiple take-offs, and their effect on the environmental impact have to be considered. Whereas it is an simple summation of the carbon emissions over all N flights to determine the total emissions,

$$CO_2 = \sum_{j=1}^{N} (CO_2)_j. \tag{5.5}$$

---

[2] A paper design is bound to look better than its real implementation as it inherently neglects unknown issues which are unavoidable and adversely affect the implemented system performance.

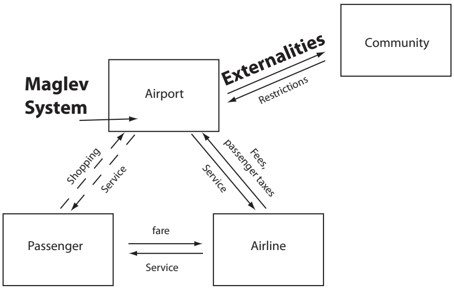


Figure 5.7: Stakeholder network used to evaluate the externalities after the introduction of the Maglev assisted take-off system.

Table 5.2: Behaviour of the stakeholders.

	Goal	**Strategy**	**Behaviour**
Airline	Maximize profit	Iterative myopic, dynamic programming	Set flight frequencies
Airport	Maximize satisfied passenger demand	Slot allocation by satisfied demand ratio	Distribute slots over airlines
Passenger	Maximize service level	Discrete choice analysis (multinomial logit)	Flight choice on frequency and availability
Community	Maintain acceptable noise levels	Kosten level lower than 35	Restrict airport slots

For the cumulative noise the Kosten level approach is used[157]as discussed in Section 4.3.4. This environmental impact is represented by the community living near the airport.

An overview of the assumed goals, strategies and behaviour for the various stakeholders is described in Table 5.2. To allow for the interaction between the various stakeholders, i.e. community, airport, airlines and passengers, in the ABMS a schedule of decision making has to be implemented. The implemented schedule might affect the simulation results[116, 134]. The decision making assumed is captured into 3 subsequent discrete events,

- *Event0*, the community allocates a number of allowable slots based on expected/ experienced noise per flight,
- *Event1*, the airport allocates the allowable slots according to the ratio of satisfied demand by the airline
- *Event2* finally the airlines make a simultaneous decision on the allocation of their budget of slots over the routes.

Event 2 is implemented as a nested scheduler to emulate the strategic behaviour. The convergence criterion, no change in airline behaviour, is supplemented by a maximum of 20 iterations. This maximum number of iterations is only reached in case of alternating behaviour and is implemented to limit excess computation times in this case. The sequence of events, for a single time step, is depicted in Figure 5.8. The equilibrium state for var-

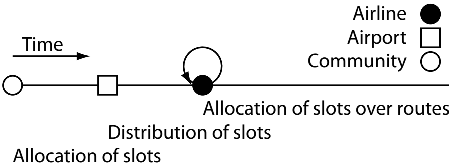


Figure 5.8: Schedule as employed in the MagLev system of systems evaluation.

Table 5.3: Assumed airline data.

(a) Cost per flight.

AL	Route				
	1	2	3	4	5
1	7106	7904	12241	-	10794
2	-	-	12065	8814	-
3	-	-	-	3743	5807
4	7986	7960	-	3883	-
5	-	-	-	3005	-

(b) Seats per flight.

AL	Route				
	1	2	3	4	5
1	140	188	140	-	188
2	-	-	173	157	-
3	-	-	-	159	183
4	183	160	-	160	-
5	-	-	-	123	-

ious scenarios is evaluated by iterating over this sequence of events until no change in stakeholder state is detected. The simulation is performed for a single day to limit the computation time. The Kosten number is based on a reference time of a year, this is achieved by assuming the daily behaviour as representative for yearly behaviour.

Scenarios

To evaluate the system-of-systems environmental impact of the technology, three scenarios are created: 1) an airport which has sufficiently low passenger volumes that the noise constraints are not reached by filling passenger saturation demand Q_m on all routes, *Not noise constraint* 2) an airport which cannot fulfill current saturation demand, but is able to satisfy saturation demand with the noise reductions achievable by the MagLev system, *Intermediate* and 3) a severely noise constrained airport, who is not expected to fulfill saturation demand, even by achieving the full potential of the MagLev system, *Noise constraint*. The three scenarios are implemented by adapting the saturation passenger demand of a simplified route structure, which is based on data from the bureau of transportation statistics[3] for Dallas Fort Worth (IATA:DFW). The evaluation is limited to five airlines and five routes to clearly show the procedure, while at the same time providing a realistic interaction between the airlines. The — arbitrarily — chosen adaptation parameters ξ are $20, 40$ and 60 for scenario 1,2 and 3 respectively. The airline specific data for the five airlines assumed are given in Table 5.3 and the route specific data in Table 5.4.

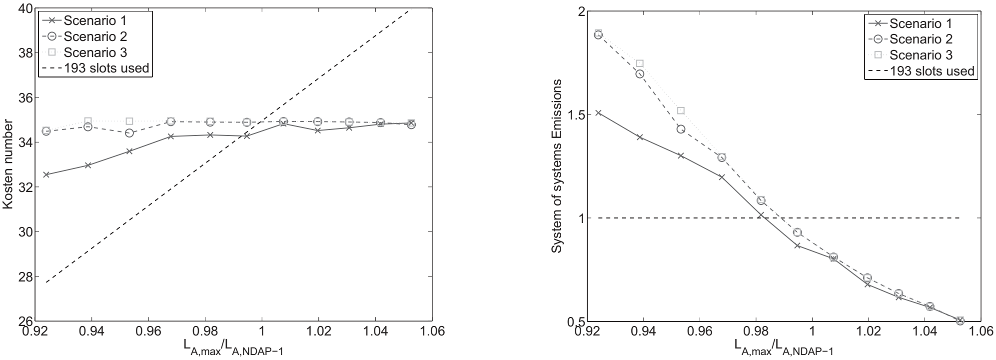
The changes introduced in the system due to the MagLev system can be summarized as follows: 1) the noise produced per flight is considered to vary between a relative noise factor $L_{A\,\max}/L_{A\,\max_{NDAP-1}}$ of 0.93 and 1.06 for initial thrust settings between 0.5 and

---

[3] http://www.transtats.bts.gov/

Table 5.4: Assumed route specific data.

Route	1	2	3	4	5
Q_r/ξ	67	119	291	379	327
p_r	181	170	260	158	149



(a) Kosten number.

(b) Carbon dioxide.

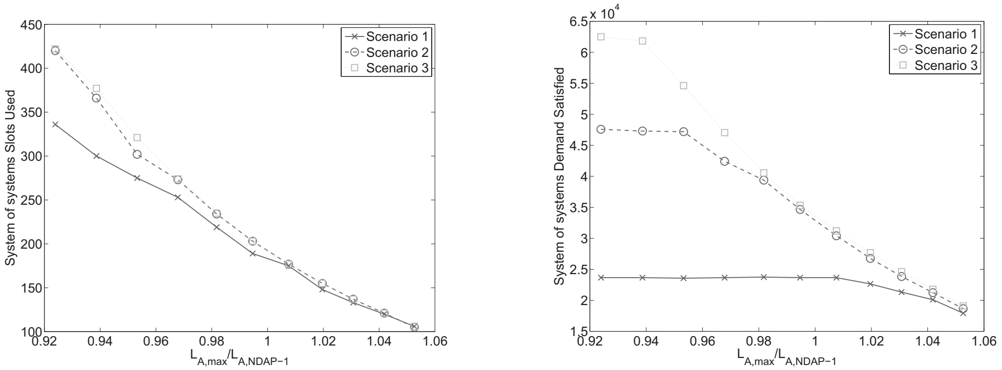
Figure 5.9: Externalities.

1.0. The reference noise in the point of consideration is $71.25dBA$, which results in 193 slots per day, i.e. approximately $70,000$ flights per year. The corresponding carbon dioxide emission reductions per flight vary between 0.88 and 0.98 with respect to the reference departure, NDAP-1. For a given noise production, the corresponding carbon emissions are interpolated from the results as shown in Figure 5.6.

Results

The questions left unanswered in the previous section are 1) how will the externalities, i.e. noise and carbon dioxide, evolve with the introduction of the MagLev system, and 2) how willing are the decision making stakeholders in accepting the MagLev system, in each of the three scenarios considered.

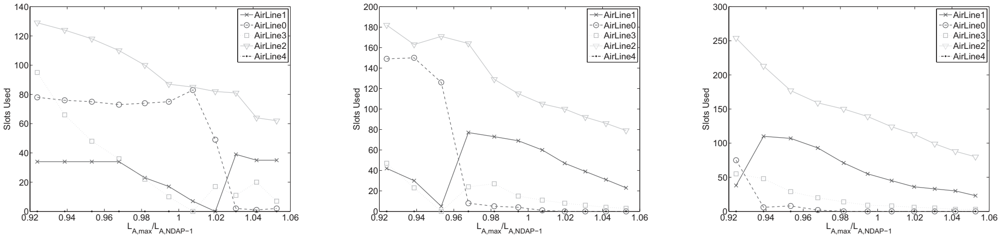
Externalities Development of the Kosten number with per flight noise, is shown in Figure 5.9a, shows a decrease for scenarios (1) and (2), which is not nearly as much as the reduction which could be achieved if the behaviour of the stakeholders would have remained constant. The reduction of the per flight noise allows for more flight movements/ slots, as shown in Figure 5.10a. These additional slots are used by the airlines to transport more passengers, i.e. reduce spilled demand, in scenario (2) and (3) as shown in Figure 5.10b. The cause for the increase in number of movements for scenario (1) is different as no demand is spilled in this scenario. This increase in number of movements should be considered strategic. That is, on a single route the airline wants to increase



(a) Slots used per day.

(b) Demand satisfied per day.

Figure 5.10: Resource usage.

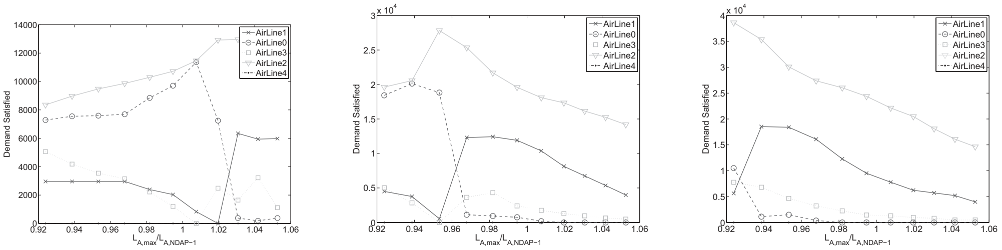


(a) Scenario 1

(b) Scenario 2

(c) Scenario 3

Figure 5.11: Flights operated per day in the three scenarios.



(a) Scenario 1

(b) Scenario 2

(c) Scenario 3

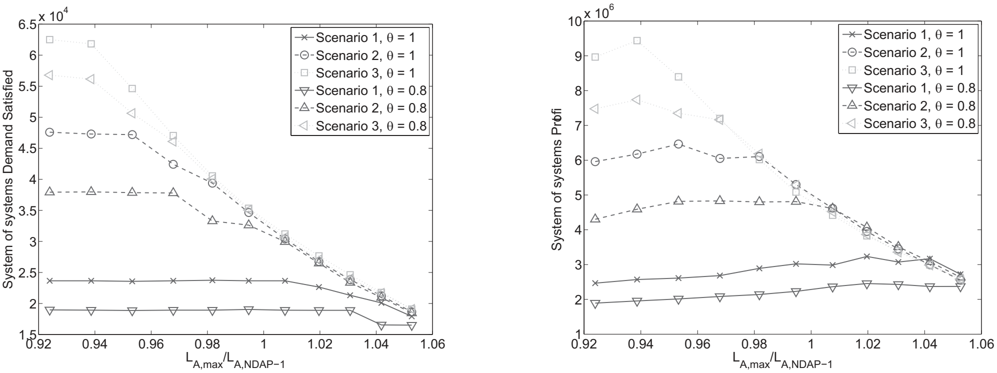
Figure 5.12: Demand satisfied per day in the three scenarios.

market share by increasing its flight frequency using the additional slots attributed to it. The resulting action of the competing airline on the route is to recapture lost market share, if permitted by the attributed number of slots. The behaviour is treated in more detail in Appendix B. The consequence is that, due to the strategic increase in number of flights, the Kosten level does not decrease proportionally to the system level noise in all three scenarios.

The carbon dioxide emissions, depicted in Figure 5.9b, are also affected by the increase in number of flights. For a similar noise level of the MagLev and reference departure — $L_{A\,\max}/L_{A\,\max_{NDAP-1}} = 1$ — the emissions are decreased, due to the decrease in per flight emissions and the constant number of flights (the SoS is controlled on noise). For a reduction of maximum noise level, the number of flights increases faster than the reduction in carbon dioxide emissions. The emission benefit at the system level has been deteriorated by behaviour at the system-of-systems level, even resulting in an adverse effect once the number of flights has increased sufficiently. Note that this example adopted the best case scenario at the system level by adopting wind power as a zero-emission power source. Adopting any other power source will aggravate the emission problem. Furthermore, the system-of-systems behaviour appears rather smooth. Focussing on the individual airline behaviour shows large changes in airline behaviour, as depicted in Figure 5.11 for the number of flights operated by each airline in each of the scenarios and Figure 5.12 for the demand.

Although these scenarios are constructed for illustrative purposes, the trend of increasing number of flights when noise constraints are relaxed by the introduction of novel technology, can be seen at, for instance, Schiphol airport (IATA:AMS)[157]. However, other constraints, as identified in Section 4.3, are likely to be encountered in the airport operation, e.g. runway or passenger capacity. Here the introduction of less noisy aircraft had only a small effect on the noise contours, but a large effect on the number of movements performed. The solution to the increase in carbon emissions would be to control for the carbon emissions. The importance of this constraint at system of systems level becomes apparent after system of systems analysis even though it appears not important from the system level. Furthermore, the general set of environmental impacts is incomplete and the consequence of increased impact for uncontrolled impacts is considered fundamental to sustainable design.

Economic impact The primary investor in the MagLev system, the airport, is assumed to base its acceptance of the novel technology on the economic benefit achieved from it. The economic benefit for the airport is assumed to originate from the additional traffic of passengers generated, i.e. Equation 4.11. The proxy investigated is consequently the number of passengers. The demand percentage satisfied is shown in Figure 5.13a. The scenarios have been constructed in such a way that demand is satisfied, will be satisfied by Implementing the MagLev system and cannot completely be satisfied by the MagLev system. Additionally, passengers might not be willing to adopt the system and the saturation demand goes down. A fraction of $\theta = 0.8$ of the original demand is assumed to emulate this. The trends for overall demand are equivalent to the original demand as shown in Figure 5.13a. For scenario (1), no additional passenger demand is satisfied, and consequently no additional revenue generated for the airport. The income from the additional flights is considered negligible, hence the investments in MagLev system are not returned by higher revenues. For scenario (2) and (3) the balance between the increased



(a) Daily demand satisfied.

(b) Total airline operating profit (Daily).

Figure 5.13: Effect of passenger adversity towards the MagLev system.

profit generated by the additional passengers, and the investment costs, the break even point is decisive for the acceptance of the technology.

The overall airline profit — $\sum_j \pi_j$ — is shown in Figure 5.13b. For scenario (1), the competition for market share, triggered by the increase in attributed slots, increases the frequency induced costs, without increasing the satisfied demand. The lower seating factors result in a lower profit. For scenarios (2) and (3) this also occurs, but only once the saturation demand is satisfied, i.e. comparing Figure 5.13a and 5.13b. For the overall airline profit it is not considered beneficial to introduce the MagLev system once saturation demand is satisfied.

5.1.4 Final remarks

The ABMS tool is shown to cope with the (simplified) intertwined stakeholder behaviour and able to translate the system level environmental impact to the system-of-systems level. This tool extends the systems engineering toolkit into the system-of-systems domain by addressing the behavioural and structural complexity of **current** behaviour. The need for such a tool is shown by the large difference in system level and system-of-systems level impact. The predicted system level impact was reduced for both noise and carbon dioxide emissions, nevertheless, the (uncontrolled) carbon dioxide emissions were increased at the system-of-systems level due to changed airline behaviour. The often used design imperative: “to reduce environmental cost, the technology efficiency should be at least as good as current technology” is found to be insufficient in reducing system of systems level impact. The systems engineering tools provide a means of designing a system in response to a perceived need or opportunity. However, the environmental impact and the need change in response to the fulfilment of this need. Conventional systems engineering does not incorporate a feedback loop in the design to address this issue. Nevertheless, the ABMS tool can be added to the systems engineering toolkit to provide this functionality and incorporate the interaction between design, stakeholder behaviour and need.

This show case illustrates that technology cannot completely solve this sustainability conundrum on its own. Especially, when economic considerations remain more important than the sustainability of actions, possibly increasing the use of technology. The success of an efficient, sustainable technology, can reduce the sustainability of the system-of-systems. Furthermore, the best technical solution with respect to system-of-systems environmental impact might not be implemented from the economic perspective. As a positive note, environmental impact is the only constraint considered in the previous simulation. In reality the airport is constraint in many other ways[86], which might be reached much quicker than anticipated. These additional constraints restrict the use growth, simultaneously decreasing the economic benefit from the technology and consequently its adoption rate and the resulting environmental cost from the increased use.

Finally, the MagLev technology example was used because of its clear and direct link to the system-of-systems level as it directly impacts multiple stakeholders. The analysis was performed as an illustrative case for the ABMS tool and the assumptions (focus on operational phase, zero emission power generation) were made to support this illustration. Nevertheless, some conclusions can be drawn on the MagLev technology. Even though take-off emissions, which were shown to increase, are only small part of the overall emissions, depending on the mission representing a fuel fraction of about 0.95. The carbon dioxide effect might therefore be minimal in comparison to the complete mission carbon dioxide emissions. Furthermore, the energy production was assumed to be emission free. Consequently, the actual emissions are even higher than predicted.

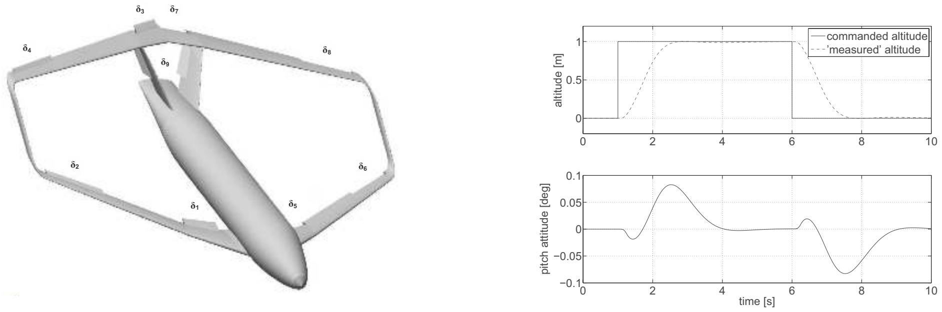
5.2 Novel behaviour: Prandtl plane

The ABMS tool used to predict the effect of stakeholder behaviour on the system-of-systems environmental impact of the MagLev system has been based on current behaviour. However, new technologies often introduce new opportunities and new behaviour of the stakeholders involved. The MagLev system design is not mature enough to predict novel behaviour. Consequently, to investigate the modelling of novel behaviour the more mature, i.e. thoroughly studied, technology of the Prantl Plane[183] (also known as the Box wing aircraft[88]) is used.

The interaction of the enabling of technologies in a changing environment is not specific to designs reducing environmental impact. The Boeing 767 became successful on long range routes, due to the Extended-range Twin-engine Operational Performance Standard (ETOPS). The Boeing 767 was the first aircraft to be certified for a ETOPS-90. This allowed the aircraft to fly routes farther than the conventional 60 minutes away from a diversion airport. The ETOPS opened up the long range over-water operation with the Boeing 767 not foreseen at is development and introduction in 1982[133].

In this example the change in technology, in particular its reliability, and regulations enabled the change of behaviour, i.e. the operation of twin engine aircraft on routes previously exclusively operated by three or four engine aircraft. Consequently, in the evaluation of a novel technology, subject to long life times, the environment is likely to change. This change in environment possibly changes the valuation of aircraft quite drastically. This is formulated by Nittinger[133] as

> *Think the unthinkable, opportunities often only show up later*



(a) Control surface layout. (b) Response to altitude command

Figure 5.14: Prandtl plane direct lift concept[64].

For novel technologies both the opportunities and the associated risks are considered larger. The opportunities are larger, since the system might enable different unforeseen behaviour increasing the value. However since the future environment is unknown the risk is higher. This risk is in addition to the technical risks of the novel aircraft project.

To evaluate the effect of the changes in behaviour a qualitative analysis on the Prandtl plane and its opportunities is performed. The Prandtl Plane concept (Figure 5.14a) employs Prandtl's best wing system to reduce induced drag. It is considered sufficiently different from conventional aircraft to have several features not present in the current aircraft fleet. Before evaluating the novel opportunities the concept is evaluated in the current environment, i.e. *ceteris paribus*. Subsequently the opportunities for alternative behaviour are investigated on the basis of changed airline strategies or goals. Finally some concluding remarks on the procedure of identification are given.

5.2.1 Concept description

The Prandtl Plane concept is an improvement over the conventional technology for current airline behaviour. That is, the environment in which the aircraft has to operate in is assumed constant in this section, *ceteris paribus*. The concept aims at a minimization of the induced drag. This induced drag minimization is achieved by emulating Prandtl's "best wing" system[146, 147]. For such a non-planar configuration, increasing the ratio between height between the biplane and the span of the configuration reduces induced drag. Of course this increases friction drag due to the larger wing connection elements (assuming constant wing loading for the complete configuration), not to mention the structural issues, which offsets the benefits from reduced induced drag[88, 183]. For the illustration of novel stakeholder behaviour it is assumed that the PP does achieve a reduced drag and/or structural weight. In cruise this reduces fuel consumption and in take-off might allow for the installation of less powerful engines, potentially reducing noise and emissions. Other possible advantages are a reduction of wing span, which would allow aircraft with larger payload volumes/ weight than the Airbus A380 to be designed without violating the current maximum airport compatibility span of 80m. However a more interesting potential not portrayed in conventional aircraft configurations is *direct lift control*[64].

Direct Lift Control A system level computational framework[187] has been used to optimize the location and size of the control surfaces[64]. For the aerodynamic analysis — performance, stability and control coefficients —, use was made of a first order, commercial of the shelf, panel code with viscous boundary layer integration[5]. The results were used in an in-house developed flight mechanics toolbox to analyze the overall behaviour of the aircraft[64]. The optimization study performed, minimized the total control surface area, whilst keeping an adequate level of control power in all axes. The resulting control architecture is presented in Figure 5.14a (note that the sizing of the wing and connecting elements was fixed). The control layout is significantly different from the conventional aircraft, with controls on both the front and rear wing. The inboard controls are mainly intended for longitudinal control and the outboard controls for lateral control. Two distinctive opportunities are provided by this architecture

1) A pure moment can be generated by deflecting the front- and rear-wing controls in a differential manner,
2) direct lift control can be applied by deflecting the surfaces on front- and rear wing simultaneously in one direction.

Combinations of both strategies are also possible. On the Prandtl Plane, the typical non-minimum phase behaviour is not necessarily present. Possibilities originating from this direct lift capability are easier precision height control and consequently easier aerial refuelling. As an illustration, the Prandtl Plane response to a altitude command is shown in Figure 5.14b. One can see that height is rapidly captured without any overshoot or non-minimum phase behaviour. Furthermore, the pitch attitude is continuously kept within $0.1\,^\circ$ from the trim value. This illustrates the direct lift capability.

This direct lift capability is one of the possible opportunities provided by the concept. These opportunities provided might invoke alternative behaviour, which might no longer fit the current and implemented stakeholder utility functions in the ABMS framework. This either requires an adaptation of the previously implemented agents or addition of a novel type of agent. In order to implement possible agent adaptations, the alternative goal/ objective function and strategy, have to be identified. To complete the information on the novel technology, the system environmental impact is to be identified. Summarizing, system level performance considerations, i.e. reduced induced drag, might result in increased performance for conventional use, however the additional features of the technology provide the opportunity for alternative behaviour invalidating *ceteris paribus*.

5.2.2 Alternative behaviour

The minimization of drag is a typical systems level optimization issue[149, 182], whereas the other specialities of the concept might lead to changes at the system of systems level. One of these changes is unexpected stakeholder behaviour, which is addressed in more detail in this section. As discussed in chapter 3, it is difficult to identify, classify and capture behaviour in a mathematical or descriptive behavioural model. The inference for novel behaviour, either due to changed goals or strategies is considered even more difficult, because the behaviour is unanticipated. Because this behaviour is unanticipated and quantitative representation is considered unfeasible, also the contribution of the technology features to a sustainable future for aviation is difficult to assess. However, being aware

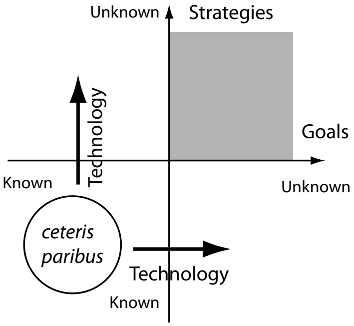


Figure 5.15: Considered influences on portrayed behaviour.

of this unanticipated behaviour and its origins, allows for improved resource allocation in novel technology projects.

Taking the Prandtl Plane as an example both the strategy — for constant goal — and the goal — for constant strategy — are evaluated. The technology as an enabler for changing goals and strategies is shown in Figure 5.15. Note that the marked area is not considered but does exist. The previous section discussed the area marked with *ceteris paribus*. The following sections discuss potential novel strategies and goals for the Prandtl plane concept.

Strategy change Conventional aircraft use elevators to trim the pitch attitude of the aircraft in flight. The pure moment and pure force generation by the PP configuration allow this trimming to occur at lower additional drag during cruise. Controlling the aircraft during cruise to reduce this annoyance can more easily be achieved using the Prandtl Plane control concept. That is the goal remains constant but the strategy (i.e. options) for achieving this is changed. In order to determine the added value of this concept requires the input of the airlines.

Goal change Alternative behaviour due to an alternative goal extends beyond the current market considered. The changed goal, due to the decomposition based on stakeholder goals, inherently results in a novel stakeholder and consequently in a market not yet considered. On a long stretch the Prandtl plane concept might provide a novel platform for in air refuelling where its benefits for increased aircraft attitude control might have significant advantages.

5.2.3 Concluding remarks

Although the identification of opportunities and drawback and the consequent alternative behaviour of the Prandtl Plane concept is far from complete. Some remarks can be made:

- Most identifiable changes are limited to the detail level. Nevertheless, changes at system level are likely to occur due to the long project and aircraft life times.
- Technologies might be deployed in alternative markets, e.g. unmanned aerial vehicles. This opens up new opportunities[32] and stakeholder requirements. This also affects other stakeholders and environmental impacts.

For both remarks the following applies: the likelihood of any change being implemented, or behavioural change in general, is determined by the costs of this change to the stakeholders[133, 166].

The agent based simulation approach is flexible enough (easily changeable agent behaviour and relations) to introduce new insights in behaviour. This causes the difficulty of predicting environmental impact to be in the identification of stakeholder behaviour and not the implementation of it in the ABMS environment. A three step approach is proposed to identify the changing behaviour in response to a novel technology.

1) Identify goals and strategies underlying behaviour of stakeholders, as well as possible changes enabled by the technology implemented in a concept
2) Implement this behaviour in the agent based simulation. This requires a value function or decision rules based on airline desires (communication). This requires a sufficiently detailed and realistic concept to allow the trade-off between benefits and drawbacks.
3) Evaluate the resulting interactions and changing properties at the system-of-systems level.

The key element in this is procedure is communication. The aircraft manufacturer knows what he can offer, but lacks knowledge on what should be implemented. Whereas the airline knows what is desirable but might lack the information what might be possible. This latter is becoming more evident as the technical knowledge of airlines is decreasing due to decreasing technical staff[166]. In order to facilitate this communication a sufficiently detailed concept is required. This requires addressing the complexities at the system level for which QFD, VE and MDO have been proposed.

Chapter 6. Blended wing body optimization: B,S complexity

> *"I have called this principle, by which each slight variation, if useful, is preserved, by the term of Natural Selection."*
> Charles Darwin.

Proposed novel technologies to address the environmental issues of aviation — e.g. Prandtl Plane and Blended Wing Body — are closely coupled. Coupled in this context means that in order to improve the system performance on a single function, the design changes significantly affect the performance on other functions. This requires an integrated approach to the design and optimization of the system as well. As an illustrative example the Blended Wing Body (BWB) is considered. The focus of this chapter is on the behavioural and structural complexity of the design process and the proposed Bi-Level Integrated System Synthesis (BLISS) approach to address this. The validity of the models to implement the BLISS approach and the complexity encountered when trying to capture real system behaviour in computation models is left Chapter 7 and Chapter 8. The goal of this chapter is to illustrate the implementation of the BLISS tool and its ability to address behavioural and structural complexity in the design and optimization of a novel technology, using a realistic example: the BWB.

Previous studies on the BWB have revealed the coupled nature of the design problem as well as the potential benefits emerging from synergy. These will be discussed in the first section. The BLISS framework has been introduced in Section 3.2, and is considered to address the behavioural and structural complexity inherent to the design of the BWB. This should allow the designer to benefit from the synergy in the design. The description of the BWB design in the model design space is described in the second section, including a description of the disciplinary modules and the parametrization chosen. Finally the implementation and verification of the BLISS framework and the results obtained from the BWB optimization are discussed.

Figure 6.1: Artist impression of the Blended Wing Body concept as described by Liebeck[104]. [Image courtesy of NASA.]

6.1 Blended Wing Body design challenge

The aerodynamic efficiency, represented by $M(L/D)_{\max}$, of long haul transport aircraft has not changed significantly in the era for the 60s to the 80s[104]. The blended wing body (BWB) concept depicted in Figure 6.1, has been conceived at the end of the 80s at Boeing by Liebeck and further investigated at the NASA Langley research centre in order to improve aircraft aerodynamic efficiency[104, 145]. Aerodynamic efficiency is improved in this concept by combining the minimum wetted area of the flying wing and the payload volume of the conventional aircraft. As a consequence, the blended wing body main challenge is finding the right balance between reducing the wetted surface area while maintaining payload volume carrying capabilities of the aircraft. The proposed concept carries additional potential performance benefits:

- Decreased wave drag, caused by favourable area ruling,
- Reduced wing loading, which affects stall speed, turn radius and airfield performance. This reduces the need for trailing edge flaps,
- Reduced wing root bending moment due to the spanwise distributed payload,
- Reduced noise level, due to above wing engine placement and resulting noise shielding,
- Reduced number of parts, due to integrated nature of the construction.

Obtaining these potential *synergetic* benefits for a feasible design also pose the main challenge for this concept. The challenge in achieving the maximum potential from the multi-function elements is illustrated by considering the fuselage. The fuselage provides a payload carrying function, lifting function and (pitch) control function. A change in fuselage geometry, for instance to increase the payload volume, is not limited to this payload, but directly affects the aerodynamic performance, engine performance and stability and controllability. This increase in functions within components, to decrease the number of components themselves, results in an increase in system structural complexity, and subsequently behavioural complexity since the behaviour of the complete system becomes more difficult to predict. Specifically, the conventional aircraft decomposition into distinct single function elements is insufficient[191]. This design difficulty makes it a challenging concept suitable for evaluation of the BLISS framework since this MDO approach facilitates the decomposition of the elements while maintaining their interconnectedness.

6.2 Model design space

The integrated nature of the BWB concept presents special design challenges. In particular the close coupling between the disciplines requires a simultaneous treatment of the various aspect systems during the design. This simultaneous approach is facilitated by the BLISS multi-disciplinary design optimization framework. In order to treat the design, the complete design space has been reduced to the technical solution of the BWB. To represent the real BWB in the BLISS framework requires a reformulation into a set of parameters and models describing the *model design space*. This translation is imperfect due to the limited number of aspects of the system represented by discipline models in the model design space.

The objective function on which the concept is compared to the alternatives, initially within the model design space (MDO) and subsequently among design solutions (VE), is determined by the requirements of the stakeholders. This choice determines the subsequent constraints and should allow for a *fair* comparison of concepts. Fair means that the objective function should measure the actual benefits of the concept for the stakeholders and not an often used proxy based on traits of conventional technologies. The difficulties in identifying and formulating such an objective have been discussed in Chapters 3 to 5. For this chapter it is assumed that an objective function and constraints for which the BWB is designed are formulated and assumed to be an appropriate representation of the stakeholder needs and requirements.

Furthermore, due to the imperfect and limited translation from design space to model design space, the selection of the models describing the model design space should at least include the important characteristic properties of the BWB. Being aware that this novel concept provides new challenges and opportunities, the BWB is initially represented by traditional discipline models[149, 182], complemented by dedicated models. These conventional discipline models are generally not created for use in a multidisciplinary environment. As a consequence their inputs and outputs generally do not “match” and some “translation” is required.

6.2.1 Objective function and constraints

In Chapter 4, a preliminary value function for the airline with respect to the aircraft is derived. In particular the costs of this aircraft in the operational environment are identified as important factors. To limit the amount of disciplines for illustrative purposes, this objective is translated into a proxy for these operational costs. However, the objective function has to account for the effect of the drag and structural weight. The drag is averaged over 4 flight conditions, 1) climb-out, 2) beginning of the cruise, 3) end of the cruise and 4) approach. Consequently, a summation of the drag in each of the mission phases is used to obtain a single objective value. To represent the relative importance of the flight phases, the drag is weighted by the time in each of these phases and normalized by the payload weight. Furthermore, the structural weight is incorporated and non-dimensionalized by the payload. The overall objective function is given by,

$$\min_{\boldsymbol{z},\boldsymbol{x}} \phi = a_1 \frac{\sum_i C_{D_i} t_i}{W_P \sum_i t_i} + a_2 \frac{W_S}{W_P}, \tag{6.1}$$

where $\boldsymbol{z}, \boldsymbol{x}$ are the design variables which are not identified yet. The two coefficients a_1, a_2 are determined by the stakeholders and obtained from the VE approach. If no conclusion on the values of these coefficients can be reached, a Pareto frontier approach can be used. For this evaluation both coefficients are set to 1. To prevent a reduction of this objective function by decreasing t_i, the mission range is constrained to a minimum acceptable range,

$$R \geq R_{\text{min}}. \tag{6.2}$$

Furthermore, the payload W_P is kept constant. This objective function and its implementation in the BLISS framework is propagated through the disciplines to determine the effect of each of the variables onto this objective. This allows the creation of a black box specific objective function as described in Section 3.2.

For the constraints three types of sources are defined, 1) originating from stakeholder requirements, 2) limitations to discipline models and 3) inconsistencies between different discipline views. Constraints of the first source are identified in the VE approach and entail items like minimum payload volume, minimum range and maximum emissions. Constraints from the second source stem from the computational approach and the models implemented to emulate the real system behaviour. Examples include the divergence of numerical models for certain conditions they are not suited to handle. One example would be the computation of the boundary layer transition point on an airfoil using a potential model coupled to a boundary layer solver. For the optimization framework to operate either the model capability has to be improved (i.e. convergence guaranteed) or, if it is considered that the set of inputs resulting in model divergence, is of no interest, the model design space can be constrained. Constraints in the last category stem from the decomposition of the real system into its aspect systems. This decoupling can result in a divergence when determining the dependent variables using an iterative approach. Mathematically it is possible that no solution, i.e. $\boldsymbol{y} = \boldsymbol{y}^*$ can be found for a set of $\boldsymbol{x}, \boldsymbol{z}$. This inconsistent design is of no interest in the BLISS routine and the model design space should be constrained to exclude this situation. The latter two constraint sources require a thorough understanding of the limitations of the model and their interactions and require disciplinary expert opinion to identify and predict. Furthermore, the model design space might be too constrained due to these “model induced” constraints and require a careful consideration whether the models chosen to emulate the system behaviour represents the actual system behaviour in the regions of interest.

6.2.2 Disciplinary models

In order to represent the characteristics of the BWB in the model design space, a selection of disciplinary models is required. To be able to analyze the performance of the proposed design, i.e. one set of possible values for the design vector $\boldsymbol{x}_D$, on the stakeholder requirements, each requirement is to be represented in the model design space, as either bound, constraint or objective. This implementation is not unique as various mathematical formulations can be considered appropriate. As an example, the objective might be considered to minimize the weight and constrain the drag, whereas the minimization of drag for a constrained weight might be equally appropriate, depending on the functions of the design. In addition to this, evaluation of *all* requirements is considered not achievable in the conceptual design phase. A a result, only the driving design requirements are represented in the model design space. Note that which requirements are driving the design is not known in advance for a novel design, due to the behavioural, structural and evaluative complexity at the system-of-systems level. These issues are addressed by the value engineering approach. Consequently, the set of chosen models is considered to emulate the real system behaviour in this BLISS approach. The ideal model design space represents all important characteristics of the design in the conceptual design phase. However, more often the implementation of the disciplines is based on availability of information. As a first estimate the following conventional selection for discipline models incorporated into computational modules has been made: *Aerodynamic performance*, *Structural strength*, *Propulsive performance* and *Weight and balance*[73].

Aerodynamic performance

The aerodynamic performance module determines the longitudinal distribution of aerodynamic forces and moments for a set of trimmed flight conditions emulating the complete mission of the aircraft. Furthermore, the aerodynamic performance module determines the aerodynamic loading distributions at the edge of the flight envelope to support the structural strength calculations.

The implemented aerodynamic model is based on the vortex lattice method[118] and captures the linear aerodynamic part of the BWB lift, accounting for control surface and high lift device deflections. The maximum wing lift is based on the local maximum airfoil lift, calculated using a panel method coupled to a boundary layer solver[50]. Finally, an estimate for the drag is based on a flat plate drag estimate, as defined by Raymer[149], where the transition point is provided by previously mentioned coupled panel method[50]. The geometry used for the aerodynamic model is shown in Figure 6.3a and will be explained in the corresponding section. In order to determine the lift and drag in each of the points of interest in the cruise flight, the aircraft is trimmed to determine the appropriate, angle of attack and control surface deflections to satisfy $\sum M = 0, L = W, T = D$.

Structural strength

The structural strength module determines the internal normal and shear stresses based on the externally applied loads and the structural geometry. Furthermore, the maximum allowable loads are determined based on the material properties and structural geometry. Finally the material volume is provided, which combined with the material density results in an idealized structural weight. Furthermore, the internal volume of the construction can is determined, resulting in the payload volume and available fuel volume.

The structural model is based on the idealized structures model described in Megson[113]. The actual geometry is replaced by an equivalent structure of booms and panels. In this equivalent structure, the booms carry the normal stresses, whereas the shear panels carry the shear stresses. The geometry used for the structural strength model is shown in Figure 6.3b and will be explained in the corresponding section.

Propulsive performance

The propulsive module provides the available thrust and engine weight and evaluates the BWB airfield performance.

The propulsion model is based on a previously developed tool by Kok[95]. This tool is based on a 0–dimensional thermodynamic component analysis.

Weight and balance

The weight and balance module provides the maximum take-off gross weight as well as the operating empty weight and the centre of gravity positions.

Except for the structural and engine weight, the weight module determines the weight of system components based on the empirical method described by Raymer[149]. Consequently it is assumed that the system weights, e.g. air conditioning, APU and fuel system, can be approximated by their conventional aircraft counterparts. The weight of the BWB specific parts, wing and engine, are computed in the structures and propulsive performance module respectively. Furthermore, this module determines the centre of gravity along the longitudinal and vertical axis,

$$\boldsymbol{x}_{CoG} = \frac{\sum_i W_i \boldsymbol{x}_i}{\sum_i W_i} \tag{6.3}$$

the lateral center of gravity position is assumed in the plane of symmetry.

6.2.3 Parameterisation

The four modules previously discussed do not necessarily represent the same system[101]. It is possible to input an airfoil shape in the aerodynamics model and a different on in the structures model, without additional provisions. The BLISS framework requires a set of views that describe a consistent system. To obtain consistency a consistent geometric description of the system by parameterisation is employed. This parameterisation provides a basic geometric description of the system from which the model inputs are derived, thus providing a consistent description in the framework input. The parameterisation should determine the inputs of the modules previously described, as depicted in Figure 6.2. For consistency in the model inputs, the system analyzer (SA, in Figure 3.8) employs an iterative procedure until the system is consistent, i.e. $\boldsymbol{y}^* = \boldsymbol{y}$. The number of x and z variables to describe the BWB in the current implementation is defined in Hendrich[73]. This set uniquely describes the geometry of the BWB in sufficient detail for the discipline models;

1) Aerodynamic performance, $\boldsymbol{x}_1$; $2N + 4$
2) Structural strength, $\boldsymbol{x}_2$; $10N + 3$
3) Propulsive efficiency, $\boldsymbol{x}_3$; 5
4) Weight, $\boldsymbol{x}_4$; 0
5) System, $\boldsymbol{z}$; $3N$.

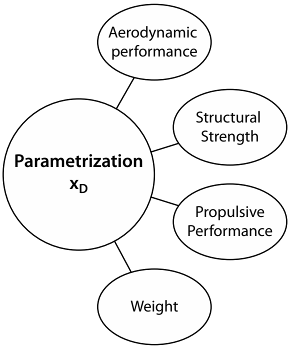
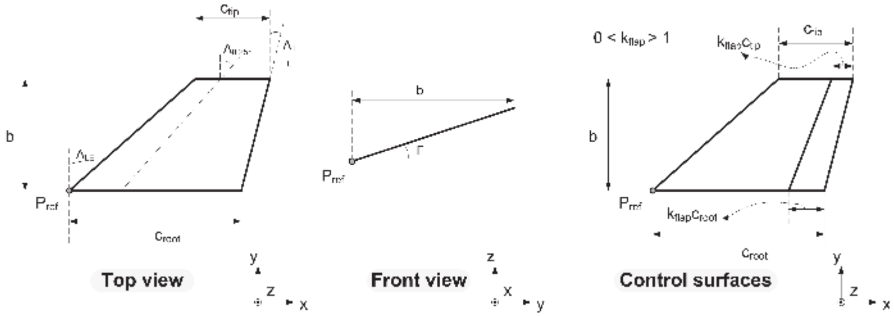
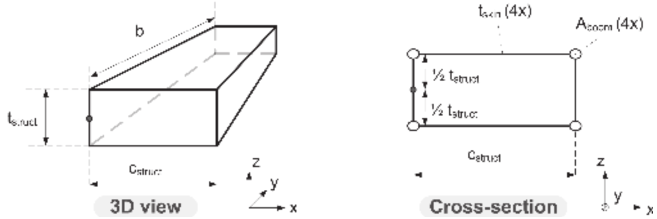


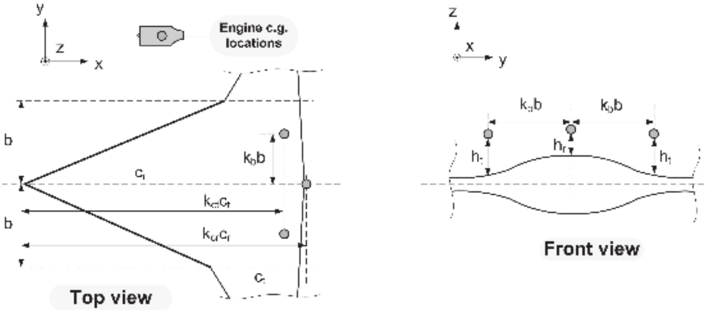
Figure 6.2: Parameterisation of the BWB model design space.



(a) Aerodynamic performance.



(b) Structural strength.



(c) Propulsive orientation.

Figure 6.3: Definition of the geometry describing variables used.

This results in a total of $15N + 12$ independent variables. N is the number of elements describing the blended wing body geometry, i.e. wing trunks. This implementation employs $N = 5$, resulting in 87 independent variables. This is a considerable design problem, however still limited with respect to a real design problem, but in the same order as Wakayama[191], who uses 134 design variables.

6.3 BLISS implementation

The BLISS framework as discussed in Section 3.2 has been implemented in order to provide a test case on addressing the structural and behavioural complexity at the systems level. This requires the implementation of the framework to be verified before conclusions can be drawn on the results of the optimization routine.

6.3.1 Constraint implementation

The constraints can be evaluated at either the black box level or the system level, by the black box optimization and the system level optimization respectively. The choice of their level of application is based on the sensitivity to the $\boldsymbol{x}_i, \boldsymbol{z}$ variables. In case of non-zero sensitivity to $\boldsymbol{x}_i$ the ith blackbox level is selected. In case of non-zero sensitivity to $\boldsymbol{z}$ and zero sensitivity to $\boldsymbol{x}_i$ the system level optimization is selected. Finally, a decision has to be made on the treatment of the constraints in the optimizer, i.e. 1) actual or 2) linearized. The large influence on computation time means that, instead of the actual constraint $g(\boldsymbol{x}, \boldsymbol{z})$, its linearized approximation is used,

$$\bar{g}(x + \Delta x, z) = g(x, z) + (d(g(x, z), x) + d(g(x, z), y)D(y, x))\Delta x \tag{6.4}$$

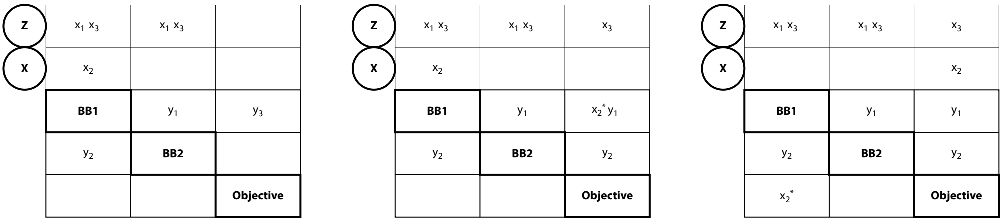
and at the system level

$$\bar{g}(x, z + \Delta z) = g(x, z) + (d(g(x, z), z) + d(g(x, z), y)D(y, z))\Delta z. \tag{6.5}$$

This increases the computational burden in the black box sensitivity analysis (BBSA) and the system sensitivity analysis (SSA), but significantly reduces the blackbox and system level optimization time.

6.3.2 Framework verification: Case 1

The implementation of the BLISS framework is verified using a test case whose optimum is known and each system condition ($\boldsymbol{z}, \boldsymbol{x}, \boldsymbol{y}$) can be determined without too much compu-



Z	x_1 x_3	x_1 x_3	
X	x_2		
	BB1	y_1	y_3
	y_2	**BB2**	
			Objective

(a) Integrated DSM.

Z	x_1 x_3	x_1 x_3	x_3
X	x_2		
	BB1	y_1	x_2^* y_1
	y_2	**BB2**	y_2
			Objective

(b) Alternative 1 DSM

Z	x_1 x_3	x_1 x_3	x_3
X			x_2
	BB1	y_1	y_1
	y_2	**BB2**	y_2
	x_2^*		**Objective**

(c) Alternative 2 DSM

Figure 6.4: Design structure matrices as implemented for framework verification.

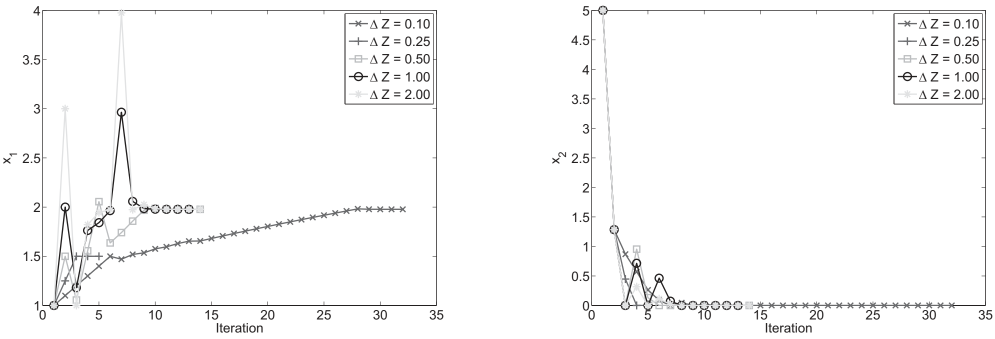
tational effort[143],

$$\begin{aligned} \min_{\boldsymbol{x}} \quad & x_2^2 + x_3 + y_1 + e^{-y_2} \\ \text{where} \quad y_1 \; & = x_1^2 + x_2 + x_3 - 0.2y_2 \\ y_2 \; & = \sqrt{y_1} + x_1 + x_3 \\ \text{s.t.} \quad g_1 \; & = \frac{y_1}{3.16} - 1 \geq 0 \\ g_2 \; & = 1 - \frac{y_2}{24} \geq 0 \\ & -10 \geq x_1 \geq 10, 0 \geq x_2 \geq 10, 0 \geq x_3 \geq 10 \end{aligned} \tag{6.6}$$

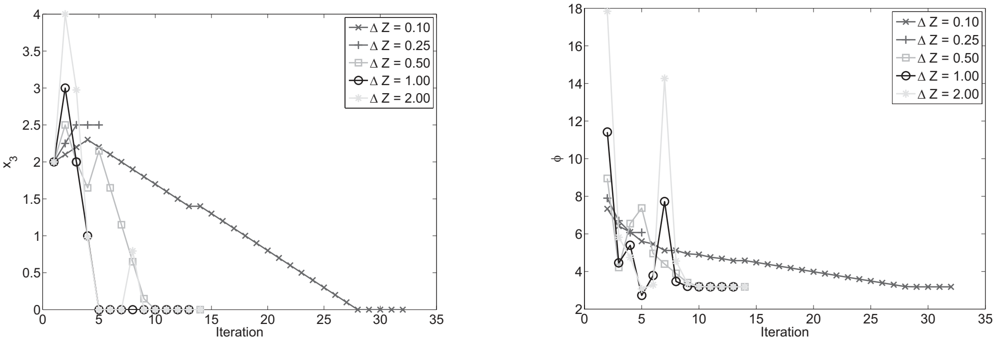
The initial condition $\boldsymbol{x}_0 = [1, 5, 2]$ and $\boldsymbol{y}_0$ = [4,10] is chosen in correspondence to Perez, Liu and Behnidan[143]. The minimum value is located at $\boldsymbol{x} = [1.9776, 0, 0]$ for a value of $\phi = 3.1834$.

Three implementations are investigated; *integrated*, *alternative 1* and *alternative 2*. The integrated approach addresses both the y_1 and objective function y_3 in BB1 and y_2 in BB2. The resulting DSM is shown in Figure 6.4a. The alternative 1 approach allocates the computation of y_1 to BB1 and y_2 to BB2 and the objective function to Objective as shown in Figure 6.4b. In order to obtain an local variable, local control over x_2 is attributed to BB1, passing it directly to the Objective as x_2^*. The alternative 2 approach allocates y_1 to BB1 and y_2 to BB2 and the objective function to objective as shown in Figure 6.4c. In order to obtain an local variable, local control over x_2 is attributed to Objective, passing it directly to BB1 as x_2^*. For the first two approaches, g_1 is evaluated in BB1 **and** system level and g_2 at system level. For the third approach, both constraints are evaluated at the system level. The implementation choice, i.e. structures, show the designers influence on the implementation of the mathematical formulation in the BLISS framework. For this analytical formulation, the actual constraint values are used. Both the *Integrated* and *Alternative 1* implementations provide the same results, whereas *Alternative 2* is not able to converge. For the integrated approach the results are shown in Figure 6.5. The restrictions imposed by the move limits show the slower convergence towards the optimum and even the prevention from reaching it ($\Delta \boldsymbol{z} = 0.25$).

In order to limit the computational burden of the constraint evaluation as well, the constraints are linearized at the system level, i.e. *hybrid*, or at the system and black box level, i.e. *linearized*. The results of this optimization implementation are shown in Figure 6.6a and Figure 6.6b for the integrated structure. It is clear that for these linearized constraints the effect on the optimization for this test case is small. However, the number of iterations



(a) x_1 (b) x_2

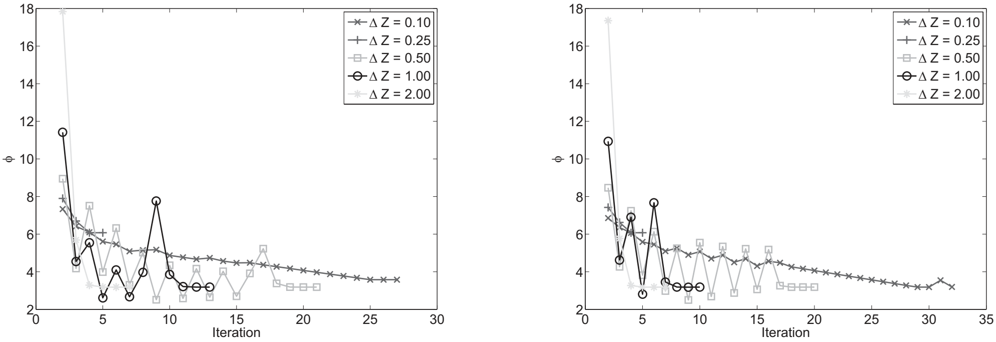


(c) x_3 (d) ϕ

Figure 6.5: Development of the $\boldsymbol{x}$ vector and objective ϕ for various z move limits. Initial point $\boldsymbol{x}_0 = [1, 5, 2]$.

as well as the per evaluation resource use has decreased drastically. Still the too strict move limits prevent the optimum from being found. Therefore various initial points and move limits need to be tried to arrive at the optimum. Furthermore, the bounds appear to be problem specific. As a result the settings for the BLISS optimization, e.g. move limits, have to varied as well. The effect of various move limits on the final optimum is shown in Table 6.1, where again the too restrictive move limit of $\Delta \boldsymbol{z} = 0.25$ prevents the BLISS framework from finding the optimum solution.

The two alternative structures are also considered using the linearized formulation. Due to the total derivatives used as constraints, all constraints, i.e. their linearized representations, are evaluated in the black box optimization. This allows the BLISS framework to find an optimum for both alternative structures, *alternative 1* and *alternative 2*. These results are shown Figure 6.7. These results can be considered structure independent, as all three formulations proved the same convergence history.



(a) Hybrid formulation.

(b) Linearized formulation

Figure 6.6: Objective function development for two constraint implementations, structure *integrated*.

Table 6.1: Results of the optimization for various move limits and two constraint implementations. Structure is *integrated*.

	Ref [143]	Actual				Linearized			
Δz		1.00	0.50	0.25	0.10	1.00	0.50	0.25	0.10
x_1	1.9776	1.9776	1.9776	1.5000	1.9776	1.9776	1.9776	1.5000	1.9803
x_2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
x_3	0.0000	0.0000	0.0000	2.5000	0.0000	0.0000	0.0000	2.5000	0.4001
ϕ	3.1834	3.1834	3.1834	6.0748	3.1834	3.1834	3.1834	6.0748	3.5778

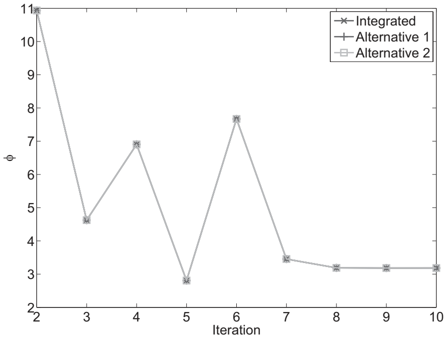


Figure 6.7: Comparison of linearized implementations, using three different structures for the objective ϕ. Initial point $\boldsymbol{x}_0 = [1, 5, 2]$.

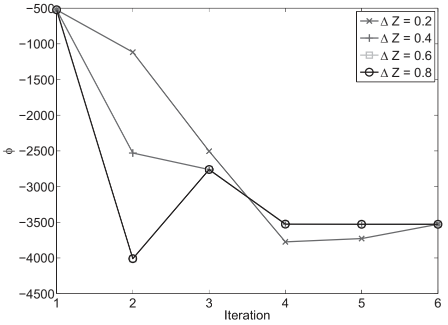


Figure 6.8: Convergence history of the objective, $-R$, for the structure dependent linearized formulation.

6.3.3 Framework verification: Case 2

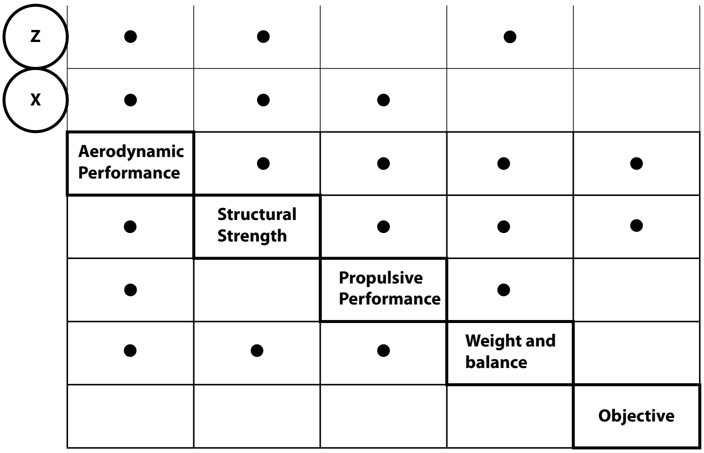
The second verification is the supersonic businessjet problem as described by Sobieski et al.[171]. This test case involves multiple black box optimizations (i.e. multiple black boxes with corresponding x variables). The linearized problem solution strategy, i.e. *all* constraints in *all* black boxes. This strategy does not provide an answer as satisfying all constraints in all black boxes using only the limited number of local variables x appears impossible. Reverting back to the structure dependent formulation, i.e. linearized constraints evaluated at their respective black boxes, provides the convergence history as depicted in Figure 6.8. This convergence corresponds well to the results as described by Sobieski et al.[171]. Consequently, the structure independent formulation does not apply to multiple black boxes as this results in an overly constrained problem at the black box level. Corrections to the linearized constraints might be applied for black box i using the Δx values for the previously evaluated black boxes;

$$\begin{aligned}\bar{g}(x+\Delta x, z)_i &= g(x,z) + \sum_{j=1}^{i-1}(d(g(x,z),x) + d(g(x,z),y)D(y,x))_j \Delta x_j \\ &\quad + (d(g(x,z),x) + d(g(x,z),y)D(y,x))\Delta x_i. \end{aligned} \tag{6.7}$$

However, this violates the intention of parallel optimization of the black boxes and is consequently not evaluated further. Nevertheless, the linearized constraints, even though the structure independent formulation is not used, provide a feasible and optimal solution. Furthermore, the results show the effect of the move limits in the intermediate iterations. However the investigated move limits all converge to the same objective value.

6.4 BWB model results

A schematic of the implemented structure is shown in Figure 6.9. This implementation and its dependencies is non-unique and is based on the availability of the disciplinary models. Optimization of the structure might therefore be possible but is not investigated further. From this figure it is clear that a distinction can be made between the local, $\boldsymbol{x}$, and the

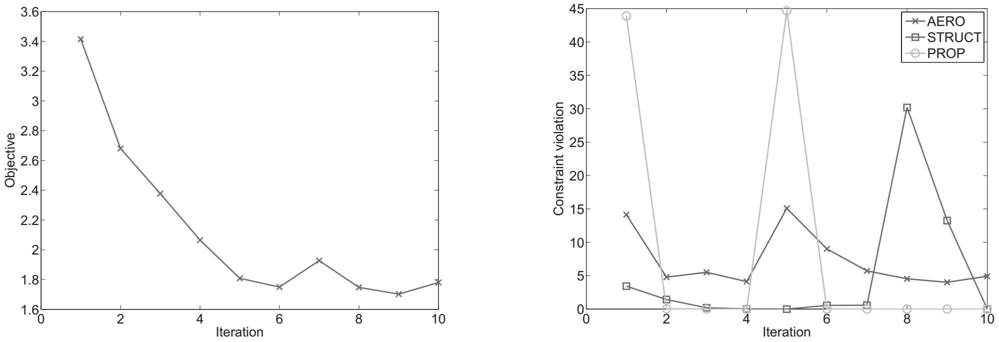


z	●	●		●	
x	●	●	●		
	Aerodynamic Performance	●	●	●	●
	●	**Structural Strength**	●	●	●
	●		**Propulsive Performance**	●	
	●	●	●	**Weight and balance**	
					Objective

Figure 6.9: Design structure matrix, adapted from Hendrich[73].

global, $\boldsymbol{z}$, independent variables. As a consequence it is worthwhile to use the BLISS framework for optimization. The total optimization problem entailed 15 z variables, 72 x variables and 114 y variables. The formulation was completed by 94 constraints, excluding the side constraints on $\boldsymbol{x}, \boldsymbol{z}$. The side constraints on $\boldsymbol{x}, \boldsymbol{z}$ are chosen rather strict to prevent the optimizer from entering the regions where the Xfoil module or the propulsion blackbox diverged.

The development of the Objective function is shown in Figure 6.10a. The objective is seen to monotonically decrease from the initial condition, meaning that the design is improved. When looking at the total constraint violation per black box as depicted in Figure 6.10b this is seen to increase for the structural strength BB and decreased for all others. This is caused by the linear formulation and decomposition of the problem, allowing the constraints to be violated. Nevertheless, the BLISS framework decreases this constraint violation while improving the BWB configuration further. No feasible solution to this formulation was found, in particular the critical Mach number on the outer wing sections could not lowered sufficiently to obtain a feasible configuration. Further iterations worsened the constraint violation as the BLISS framework tried to decrease constraint violation for the aerodynamics module at the expense of the other modules. The fact that the outer wing sections proved critical with respect to Mach number is in correspondence with the findings of Wakayama[191]. To improve the solution the model design space should be increased by making the airfoil shapes variable. This solution, as used in the MOB project[121] or in the study performed by Mialon, Fol and Bonnaud [115], of incorporating other airfoil geometries, was not investigated further. Finally, the planform as initially provided and obtained from the BLISS optimization is shown in Figure 6.11. The upper part depicts the aerodynamic planform and the lower part the structural planform. The changes in planform are small, e.g. decrease in sweep and increase in span, however their impact is significant as the objective value was improved from 3.4 to 1.8 and constraint violated was decreased from 63 to 5. This shows the sensitivity of the design to small deviations.



(a) Objective function

(b) Mean constraint violation per blackbox

Figure 6.10: Objective and mean constraint violation development over various BLISS iterations.

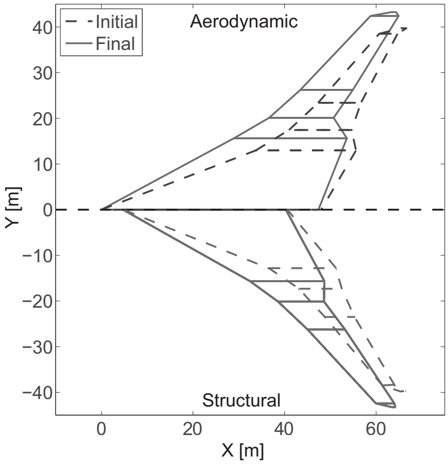


Figure 6.11: Planform development, initial and final planform. Upper part of the figure is the aerodynamic planform lower part is the structural planform

6.5 Concluding remarks

The parameterization used to describe the BWB concept in the model design space was too limited to find a feasible solution. The main limitation is caused by the focus on a single (scalable) airfoil shape. Increasing the model design space by allowing more airfoil shapes allows the design to become feasible as illustrated by the MOB study[121]. This comes at the cost of using higher fidelity modes (e.g. CFD/RANS/LES) which can capture the large sensitivity of aerodynamic phenomena for geometry. Nevertheless, the BLISS framework allowed analysing and improving the BWB design in the model design space.

Despite the infeasible BWB design, the BLISS method was able to address the behavioural and structural complexity of the BWB design problem. The problem was decomposed into multiple disciplinary models which were simultaneously optimized maintaining their interaction. Even though the BLISS framework provides an approach of using existing tools as black boxes, the implementation of the BWB in the BLISS framework showed the difficulty of transferring the various models into a design framework. As illustrated by in Case 1, the variables can be reorganized (local to global and vice versa) within limits. This simplified case with a known solution proved helpful in understanding the principles and verifying BLISS, despite it being far away from any realistic design problem in terms of number of variables, couplings, constraints and black boxes. This structuring challenge and the search for appropriate models to address the design problem is illustrated by the BWB design problem. The BLISS framework does not provide a general approach which guarantees a (best) solution. Consequently, the presented solution of the BWB is not arrived at automatically and requires human intervention not only in the search for an optimal design for a given structure, but also in the various implementation structures (model couplings and arrangements). Nevertheless, the consistent designs provided by BLISS in each of the design iterations provides sufficient information to solve/ address the issues in understandable design space (i.e. no convergence issues, different systems to be considered). This strengthens the view that the BLISS framework is a powerful guiding design management mechanism facilitating the structure to design at both the system and subsystem level.

Despite the iterative procedure required to setup the design problem, the MDO approach and BLISS in particular is a step in the right direction to address the coupled solutions. Since, MDO frameworks allow the early incorporation of multiple disciplinary views in the optimization, belief in the realism of the solution is increased. In addition to this, the integrated approach provides the opportunity to benefit from synergy.

Chapter 7. Propeller-wing-tail interaction: M complexity

> *"The beginning of knowledge is the discovery of something we do not understand."*
> Frank Herbert.

Chapter 6 dealt with the structural and behavioural complexity at the system level, addressed by the BLISS approach. These MDO approaches rely heavily on computational model representations of reality. If the sustainable solution is to be found in the complex intertwined solutions the agreement of these model predictions with the real system behaviour is important. The goal of this chapter[1] is to illustrate the procedure of determining the amount of agreement between model predictions and real system behaviour, i.e. validation to support design. For this purpose a single interaction is taken to focus on the modelling complexity and eliminate structural complexity.

Although the BWB show case used first principle models, the use of statistical methods in the conceptual design is widely adopted[149, 182]. However, the scope of statistical methods is limited to the data used to construct the models. As a consequence they are considered ill equipped to support the design of novel configurations. The more fundamental first principle based methods provide a solution but experience a large gap between their implementation, i.e. bottom up approach, and the needs in conceptual design, i.e. top down approach. In addition to this, first principle methods focussing on the main causes might be suitable to predict the system performance in a large part of the envelope, but are insufficient beyond their often linear predictions. Furthermore, since design is often based on the limits of the design itself, e.g. what conditions cause the system to stop functioning, non-linear predictions are required as well. To address this gap, many quantities are estimated and tested/validated during the conceptual design, using an iterative procedure (trial and error).

Testing of the used estimates using measurements during this conceptual design often poses a problem as many specifics required for test-model fabrication have not been decided upon. The result is that a limited number of situations, e.g. possible designs, is

---

[1] This chapter is based on work described in M.J.T.Schroijen[162].

tested from which the model accuracy is inferred. Furthermore, tests have to be redone once the design becomes more mature. This procedure encourages the application of safety factors, to compensate for phenomena not accounted for in these early stages of design and results in over-dimensioning of components and subsequent performance loss.

To investigate obtaining trust in a computational model, i.e. addressing modelling complexity, the propeller-wing-tail interaction is considered for it appears to have been “solved” since aircraft have been propelled by propellers since the first flight by the Wright brothers.[2]. In order to investigate the benefits and drawbacks of various aerodynamic force modelling methods three computational models are created. The first model is based on potential flow theory and is considered ideally suited for the conceptual design level due to low computation times and limited concept details required. The second and third models are a Reynolds Averaged Navier Stokes (RANS) models, suited for incorporating the influence of more geometry and flow details, at the cost of larger computation times. Further information is obtained from wind tunnel measurements performed by Mannée[107, 108], Binkhorst[22] and Schroijen[160, 162]. Finally, statistical methods as described in the Engineering Sciences Data Unit (ESDU) are used to complete the information for comparison.

First information required from the model for the design is discussed. Second, an investigation on available measurement results is given in Section 7.2. Section 7.3 proposes three mathematical models which are validated in Section 7.4.

7.1 Vertical tail design

The vertical tail design involves issues from various disciplines. The range performance of the aircraft is affected by the vertical tail design by the tail weight and drag. The aerodynamic analysis of the vertical tail involves interaction with the wing trailing vortex sheet as well as interaction with the fuselage. The resulting forces and moments have an influence on the loading of the structure as well as the stability and control. Stability and control evaluations on the other hand require forces generated by the vertical tail to maintain desirable aircraft characteristics inside the flight envelope. This limited treatment, depicted in Figure 7.1, shows the coupling between disciplines for this specific case. The current treatment limits itself to the dashed box, focussing on obtaining aerodynamic forces and moments generated at the aircraft system level by a certain vertical tail design.

7.1.1 Conceptual design of the vertical tail

Conceptual design of multi-engine propeller aircraft has been complicated by the interaction between the propeller slipstream and aircraft. Torenbeek[182, pp.331-339] notes that with respect to propeller aircraft

> “the yawing and rolling moments induced by engine failure present control problems and downgrade the flight performance, in particular when the engine fails in the takeoff.”

Raymer[149, pp.261-263] also notes that

---

[2] A large part of this chapter is based on Schroijen, Slingerland and Veldhuis[162]

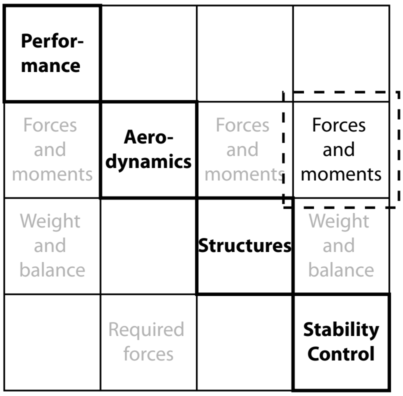


Figure 7.1: Focus of the current analysis tool.

> “wing mounting of engines introduces engine-out controllability problems that force an increase in the size of the rudder and vertical tail.”

Vertical tailplane design is determined by stability and controllability considerations, especially in one-engine-inoperative conditions during take-off.

The contribution of the vertical tail under influence of the propeller slipstream in one engine inoperative has been summarized by Torenbeek[182, pp.333] in,

$$C_{n_V} = -\left(\frac{\partial C_{y_V}}{\partial \beta}\bar{\beta} + \frac{\partial C_{y_V}}{\partial \delta_r}\delta_r\right)\frac{l_V}{b}, \tag{7.1}$$

where the contribution of the vertical tail is split into a contribution of the vertical tail and rudder deflection. l_V is the moment arm of the vertical tail, δ_r the rudder deflection angle and $\bar{\beta}$ is the side slip angle corrected for the interference with the propeller slipstream. In particular this estimation of the side-wash component and the equivalent yawing moment are the focal point of this chapter.

Equation 7.1 shows that a significant contribution to the stability and controllability considerations is posed by the propeller-empennage interaction, by means of the propeller slipstream[107], represented in the effective side slip angle, $\bar{\beta}$. Research on this interaction has focused on obtaining relations between propeller settings and resulting stability derivatives with limited attention to the physics underlying this interaction.

Mannée[107], in an early research, showed that there is a significant contribution to the yawing moment of an aircraft, in one engine inoperative condition, due to the interaction of propeller slipstream and vertical tail. Stuper[175] had already identified that the wing significantly alters the propeller slipstream. In order to quantify this effect, he performed measurements in the wake of a jet-wing and a propeller-wing combination. More recent experimental research by Veldhuis[189], Gamble and Reeder[61], and Roosenboom et al.[154] has been carried out to quantify the deformation of the flow field behind the propeller and wing due to their interaction.

Further research on the propeller-tail interaction has focused on effects on either longitudinal or directional stability. Eshelby[55] modeled the effect of the propeller-wing-tail interaction on the longitudinal stability by means of a potential flow model. This model was, however, limited to the effect of the propeller's induced axial velocity and the altered wing lift distribution on the horizontal tail. Katzoff[91] has conducted experiments using various aircraft to determine the longitudinal stability, using the propeller thrust coefficient as a variable. More recently, Yang and Li[148] coupled a propeller vortex panel method with an aircraft vortex panel method obtaining aircraft longitudinal forces and moments. Eshelby[155] performed measurements to determine the thrust effects of multiple propellers on the stability coefficients of a twin engine aircraft.

Consequently, the coupled nature of the aerodynamic components, propeller, wing, fuselage and tail, and the incomplete information available in open literature result in uncertainty in the design of the vertical tail. Furthermore, the incomplete information set is further limited for use in the conceptual design by the specific cases treated. That is information obtained from the specific cases can only be generalized, i.e. extrapolated to concepts outside the tested set, by a thorough understanding of the underlying physics.

7.1.2 General assumptions

As a starting point for the sizing of the vertical tail, the condition of equilibrium state after engine loss was used[182]. The yawing moment induced by the propeller in one engine inoperative condition has to be balanced by the vertical tail, including rudder. To be able to determine the size of the vertical tail the aerodynamic directional forces and moments in one engine inoperative condition have to be determined. The air flow around the aircraft in this flight phase is generally complex, i.e. sensitive to small perturbations in geometry and flow conditions:

- The aircraft is flying at an angle of side slip resulting in non-symmetrical flow around the fuselage and wing.
- The aircraft is usually in a high lift condition which results in non-linear aerodynamic effects (low speed, high thrust) and limited controllability.
- The flow is distorted due to the inoperative engine, resulting in additional drag, especially if the propeller is not feathered.

This complex flow pattern is shown schematically in Figure 7.2. To focus on understanding the dominant phenomena a less challenging flight condition is taken as a starting point by applying the following assumptions:

- The side slip angle is set to zero, resulting in the inability to fulfil the steady condition in one engine inoperative with zero bank angle.
- The feathering state of the inoperative propeller is simulated by removal of the propeller, which means that the additional drag is assumed to be negligible.
- The aircraft is assumed to operate in the linear region of the lift curve, even with high lift devices deployed.
- The horizontal tail is not included, which decreases the stabilizing effect of the empennage on the aircraft's yawing moment[131, 132]
- The aircraft has two engines, for this configuration the propeller induced destabilizing effects in one-engine-inoperative condition are assumed to be dominant.

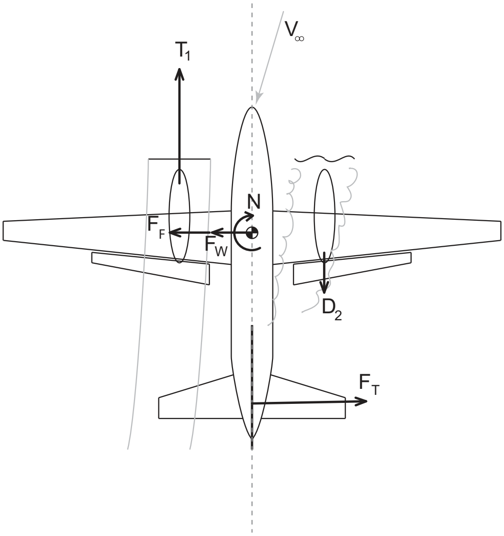


Figure 7.2: General situation of a twin engine aircraft with starboard engine inoperative. Included are the most important forces and moments acting on the aircraft components.

These simplifications are used to investigate the interaction of the propeller with the remainder of the aircraft. In particular the yawing moment coefficient of the complete configuration is of interest.

7.2 Experimental results

Experiments can only be conducted on a limited set of physical implementations of designs, on which only a limited set of physical phenomena can be considered. Modular and flexible test model geometries can be used to extend the range of geometries available for testing, however the variation in test is limited. A broad scope of data sources is therefore required for the validation of a conceptual design support tool intended to predict the behaviour in previously unconsidered designs. Tool is defined as a mathematical or computational model. Three complementary geometries and experiments are used to validate the potential flow model intended for the conceptual design phase; 1) full scale test flights on a comparable geometry, 2) dedicated experiments on the forces and moments in one–engine–inoperative condition found in open literature and 3) dedicated experiments performed for the validation of the potential flow model and understanding of the physical phenomena.

Full scale test flight

For a full scale investigation of the interaction of the propeller and aircraft, measurements have been performed by undertaking one engine inoperative (OEI) flight tests in a Lockheed C-130H-30 Hercules[132]. Assuming decomposable component contributions, the total aircraft yawing moment (c_{n_T}) can be written as,

$$c_{n_P} + c_{n_N} + c_{n_W} + c_{n_F} + c_{n_E} = c_{n_T} = 0, \tag{7.2}$$

where, the subscripts P, N, W, F and E stand for Propellers, Nacelles, Wing, Fuselage and Empennage respectively. This yawing moment equilibrium is obtained, with zero side slip angle $\beta = 0\,^{\circ}$, by counteracting the rudder side force by banking into the good engines. To achieve force and moment equilibrium an aileron deflection is also required[132]. Measuring or calculating in power off condition values for $c_{n_N}, c_{n_W}, c_{n_F}$ and c_{n_E} are obtained. Maintaining zero side-slip angle in OEI condition results in two additional contributions to the yawing moment of the rudder and ailerons with respect to power off conditions ($T = 0$), 1) a static yawing moment $\sum_i \boldsymbol{T_i} \cdot \boldsymbol{y_i}$ and 2) the additional contribution due to the propeller slipstream interference $\Delta_S c_n$,

$$\Delta_S c_n = -\left(c_{n_{\delta_r}}\right)\delta_r - \left(c_{n_{\delta_a}}\right)\delta_a + \sum_i \frac{\boldsymbol{T_i} \cdot \boldsymbol{y_i}}{q_\infty S_w b}. \tag{7.3}$$

For four speeds — $97, 100, 106$ and $124kts$ — measurements are performed on the following quantities: $W_f, h_p, \Theta, V_i, \delta_f, \phi, \theta, v_z, \delta_a, \delta_r, Q, T_i, M$[132]. From these quantities the control deflections, δ_r, δ_a, the individual engine thrusts, $\boldsymbol{T_i}$, and the dynamic freestream pressure q_∞ are determined. The geometry resulted in values for $\boldsymbol{y_i}, S_w, b$. The information set is completed by the control derivatives which are estimated using ESDU methods[132, 161]. Finally, the rotation of all four engines, numbered 1 to 4 from port to starboard, is clockwise when seen from behind.

Mannée wind tunnel measurements

Mannée performed wind tunnel measurements on a fuselage, wing vertical tail configuration for OEI. This configuration had variable wing mounting positions, high, mid and low, as well as variable engine outboard locations. The dual engine model dimensions are shown in Figure 7.3. The measurements captured three forces; lift, drag and side force, as well as the moments, roll, yaw and pitch, in various conditions. The condition of interest for the model validation is the critical aircraft configuration with respect to the additional yawing moment; i.e. the high wing, engine closest to the fuselage, flaps deflected and the aircraft at an angle of attack[107]. Although extensive measurements have been performed on the various configurations and their effects on the forces and moment in one engine inoperative condition, the investigation of the flow field causing these interferences is limited.

Dedicated wind tunnel measurements

Three types of measurements in OEI condition were performed in the low speed, low turbulence wind tunnel at the Delft University of Technology. First, forces and moments were measured to determine the power-on effects on the complete configuration. Second, sidewash was measured in front of the vertical tail to determine whether this could provide a sufficient explanation for the additional side force and yawing moment. Finally, velocity

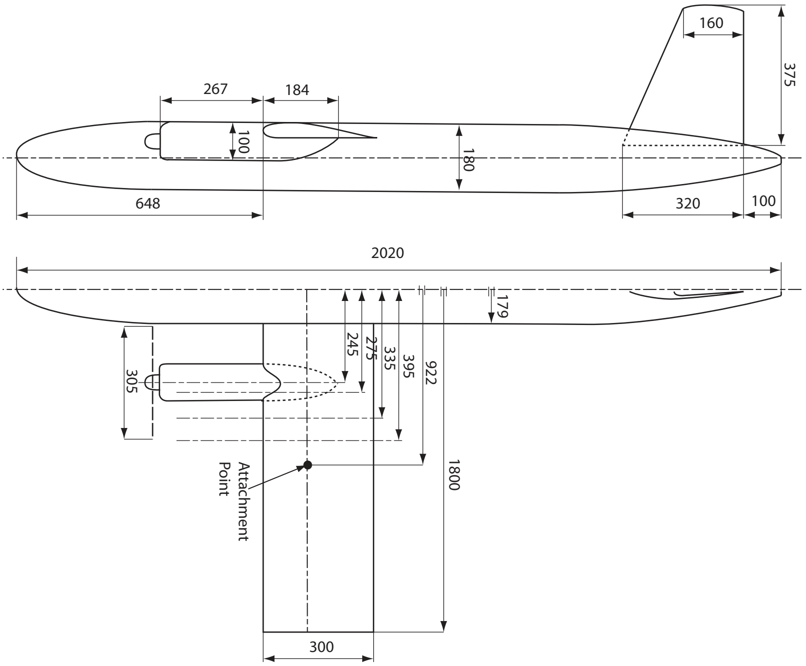


Figure 7.3: Model dimensions as tested by Mannée (figure adapted from Mannée[107])

vectors were determined behind the inboard wing, to capture the path of the inboard flap tip vortex and part of the propeller slipstream for a better understanding of the flow field behind the wing, inboard of the nacelle.

Windtunnel model description The wind tunnel model was a $1:20$ scale two engine Fokker F27 model ($b_W = 1.45m, l_F = 1.155m$), with double slotted in- and outboard flaps. The dimensions of the model are shown in Figure 7.4. The horizontal tail plane was removed for two reasons; to be able to measure in the flow field behind the wing and to reduce complexity by removing the interference effects as it has a stabilizing effect on the directional control [131, 132]. The two engines present to drive the two constant pitch propellers ($D_P = 0.183m$) were high frequency three-phase induction motors rated at $3.6kW$. In the measurements, only one of these engines was fitted with a propeller to simulate the one-engine inoperative condition. Both port and starboard engines were used for inboard (IU) and outboard up (OU) measurements, resulting in four situations. The rotation directions are defined as given in Figure 7.5.

To obtain a thrust setting comparable to a go-around manoeuvre, the advance ratio $(\frac{V}{nD})$ was kept as low as possible. This was obtained by choosing the highest practical propeller revolution speed ($280Hz$) combined with the lowest free stream velocity ($40m/s$) that prevented serious Reynolds number effects. Moreover, the propeller speed was limited by engine cooling capacity. The resulting Reynolds number based on the wing chord of $350,000$ was rather low and transition strips at 30% of the wing and fin chord were used to prevent laminar separation of the boundary layer.

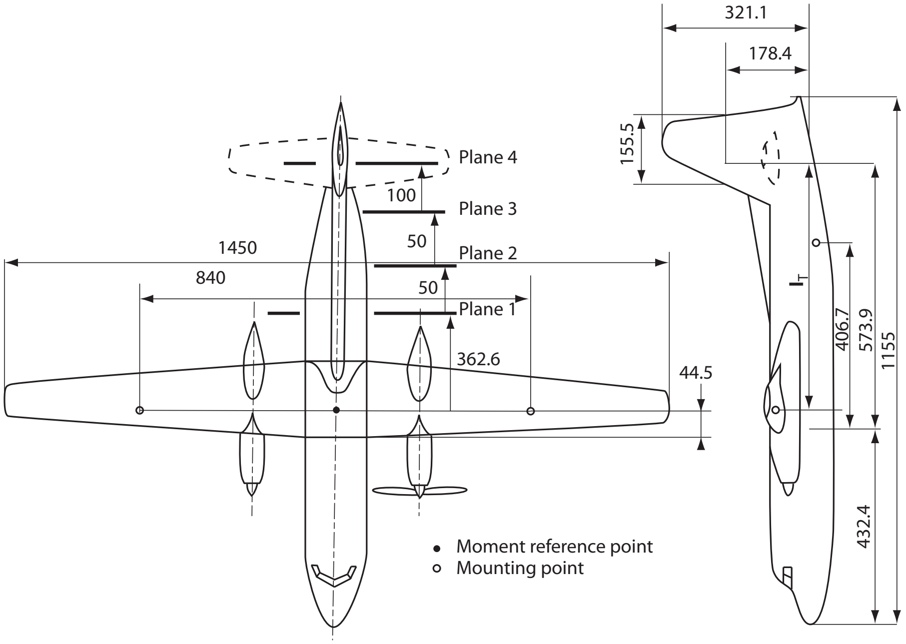


Figure 7.4: Fokker F27 model with mounting points, and the stations used for flow measurements behind the wing, adapted from Binkhorst [22].

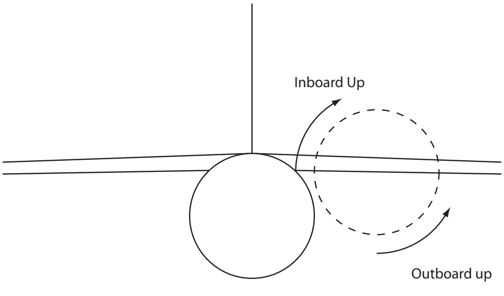


Figure 7.5: Inboard up (IU) and outboard up (OU) propeller rotation direction, aircraft seen from the front.

The measurements were performed with the inboard and outboard flaps deflected over $24\,^\circ$ at an angle of attack of $0\,^\circ$ and $6\,^\circ$ at a constant side slip angle of $0\,^\circ$.

Measurement equipment The forces and moments were measured with the wind tunnel's external six-component balance system. The model was connected to this balance system by three struts, two mounted at the wings and one at the aft body (tail strut) as depicted in Figure 7.4. The tail strut was used to control the angle of attack of the model and to feed power and coolant to the engines. The model was inverted to minimize the disturbances by the mountings as shown in Figure 7.6. A conical head, five hole probe[189], with a diameter of $1.65mm$, was used for the quantitative measurements in front of the vertical tail and behind the wing. It was calibrated in the range of $-45\,^\circ$ to $45\,^\circ$ and positioned at $1.9\,^\circ$ angle of attack and $11.9\,^\circ$ angle of side slip to reach all areas of interest. Moving the probe was done via an electronic traversing system.

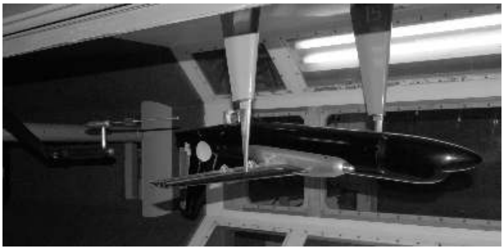


Figure 7.6: The F27 model as mounted belly-up in the wind tunnel. In the back the five-hole probe and traversing system can be seen.

Measurement data processing The balance measurements were corrected for wind tunnel wall and support interference effects. Zero measurements were performed to determine the forces and moments without propellers installed. These were subtracted from the forces and moments with one propeller installed to determine the thrust coefficient

$$T_c = \frac{S_\infty}{S_P}\left(C_D(\alpha, \delta_f, J=0) - C_D(\alpha, \delta_f, J)\right). \tag{7.4}$$

In this way the the net installed thrust coefficient was obtained. The zero installed power measurements were also used to correct for initial asymmetries in the model. The balance measurements were performed for both the starboard and port engine allowing for a correction of thrust effects on the model asymmetries, by a least squares approximation. The yawing moments are related to the static yawing moment (C_{n_S}), which is defined as the net-thrust times the moment arm. Moreover, the yawing moment coefficient is defined by the difference in moment between the configuration without propeller and with running propeller.

The sidewash measurements were performed in the plane of symmetry in front of the vertical tail as indicated in Figure 7.7, where the sidewash velocities should be zero when using a symmetrical model. The velocity vectors were, therefore, corrected for the slight asymmetries in the model and support system, by performing a measurement without propellers installed and subtracting these values from the propeller operative values.

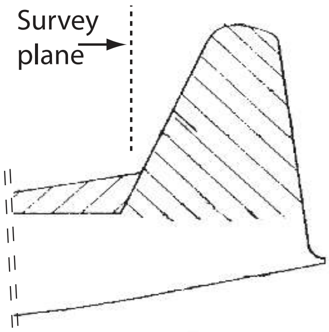


Figure 7.7: Location of the sidewash measurements in the plane of symmetry of the vertical tail.

The five hole probe was mounted such that one side of the wing trailing vortex sheet could be measured behind the propeller, wing and flap. To perform measurements on the opposite side of the operative engine, the propeller was uninstalled and installed on the opposite side instead of modifying the traversing system of the pitot probe. The measured velocities were calculated in the body frame of reference. To determine the vorticity strength a central difference scheme was used

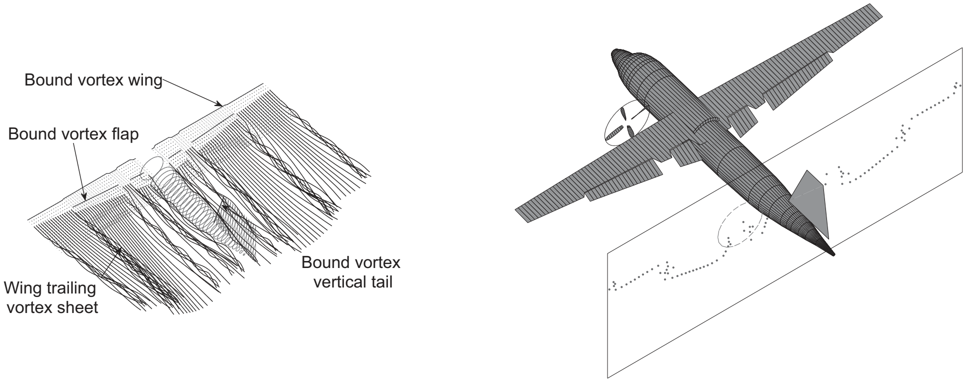
7.3 Mathematical models

To be able to use the information obtained in the experimental section in the conceptual design phase, a potential flow model is created. Potential flow models are generally fast and require little geometric detail for reasonably accurate results. Consequently, they are considered suitable for the aerodynamic modelling of the aircraft in the conceptual design phase. Furthermore, to extend the limited data available from the experiments a finite volume method. Both models will be shortly discussed in this section.

Potential flow model

The numerical aerodynamic model is based on potential methods and is described more extensively in previous work[161, 160]. The propeller is modeled by vortex theory[65] with a correction for the finite number of blades[51]. The wing, flap and vertical tail, without dorsal fin, are modeled by Prandtl's lifting line theory, including the interaction with the fuselage [63, 90, 123]. Finally, the deformation of the wing trailing vortex sheet is computed by a fourth order Runge-Kutta time stepping method[20, 96].

Since potential models have numerical difficulties due to the singularities in the elements used to model the flow, two situations have been considered, a wing trailing vortex sheet which was prescribed and without roll–up (*non–deformed*) and the time stepping method,



(a) Vortex distributions. (b) Representative geometry.

Figure 7.8: Fokker F27 geometry used in the potential flow model.

where the vortex sheet was allowed to roll–up (*deformed*). In both situations the propeller slipstream boundary was assumed to be a rigid cylinder.
The input consists of basic aircraft geometric and control parameters, employed during conceptual design, complemented by propeller geometric and control parameters, and flight condition parameters. The geometry modelling is shown schematically in Figure 7.8. The output gives the yawing moment and side force coefficient of the components and the complete configuration.

Reynolds averaged Navier-Stokes model

In order to investigate potential discrepancies, i.e. extend the experimental data, between the measurements and numerical model, a computational model has been made using the Fluent flow solver to model the configuration as measured by Mannée[107].

The propeller disc was modelled as an actuator disc with appropriate propeller induced axial and tangential slipstream velocities. The input for the RANS propeller model (fan) was set to obtain the same installed thrust as used by Mannée[107], using the vortex theory model mentioned in Section 7.3. The resulting values for the total pressure jump, ΔP_t, and the induced tangential velocity component, $v_t(r)$, were used as input in the RANS fan model[59]. The configuration employed in the RANS model is shown in Figure 7.9. The grid was unstructured with 1.7 million tetrahedral cells. Furthermore, the solver used was steady laminar, linear, with a Semi-Implicit Method for Pressure-Linked Equations (SIMPLE) coupling between pressure and momentum.

Simple wing-propeller geometry

To obtain more detailed information on the interaction between the propeller slipstream and the wing, a simple geometry is created. The wing is replaced by an infinitely thin plate and the propeller is represented by an actuator disc. The resulting geometry is shown schematically in Figure 7.10. This simplified model geometry is implemented both in a

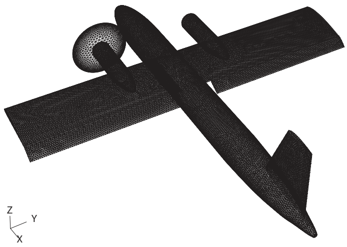


Figure 7.9: Schematic representation of the configuration as used in the RANS model and in the experiments by Mannée[107].

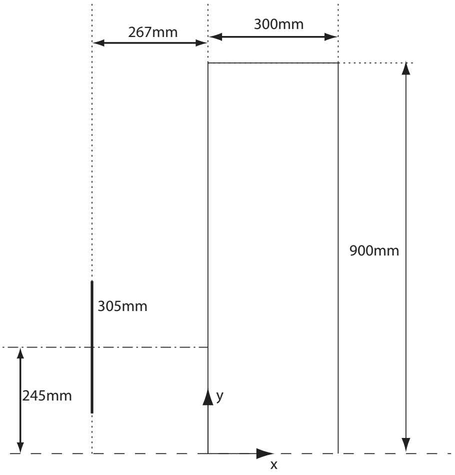
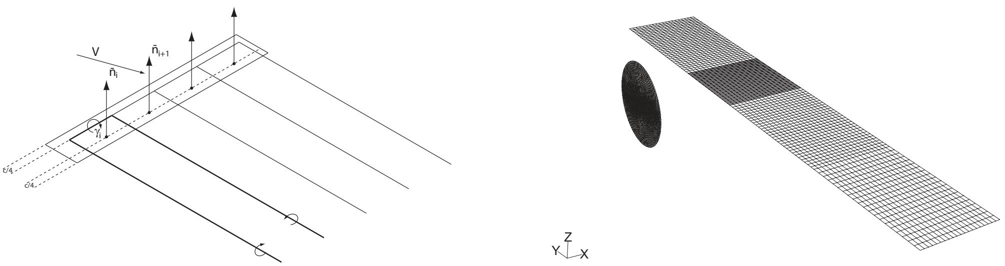


Figure 7.10: Schematic representation of the right half of the configuration investigated.

potential and a RANS model. Although this comparison cannot provide conclusive answers on the model validity, it is considered to provide a means of studying the contributions of the various model-assumptions and might consequently provide insight into the flow phenomena difficult or impossible to obtain by measurements. The respective grids for both the potential model and the RANS model are shown in Figure 7.11. For the potential model the number of vortices has been set to 100 over the wing span and 1 in chordwise direction, which is considered a good balance between accuracy and computation time for the complete potential model. The RANS grid consisted of 1.1 million tetrahedral cells. Furthermore, the grid is refined at the leading and trailing edge to capture the suction peak and trailing edge effects.



(a) Schematic of the location of vortex elements and collocation points.

(b) RANS surface grid, not shown are the refinements at the leading and trailing edge.

Figure 7.11: Surface grid used for potential flow and RANS model

Table 7.1: Sources of data used.

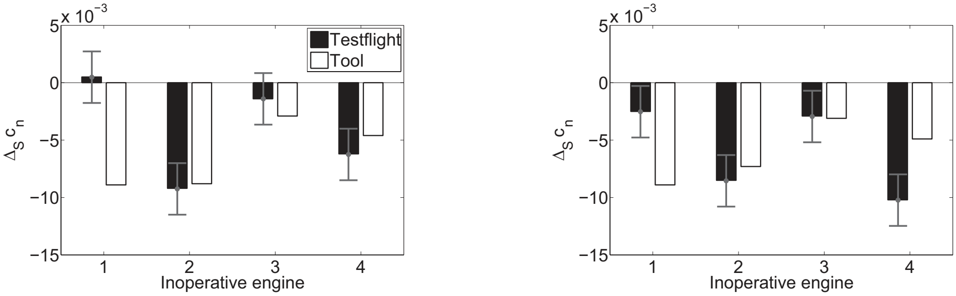
	Geometry			
Source	Wing propeller	Fokker F27	Mannée	Hercules
Potential	•	•	•	•
RANS	•		•	
ESDU		•	•	•
Wind tunnel		•	•	
Full scale				•

7.3.1 Summary

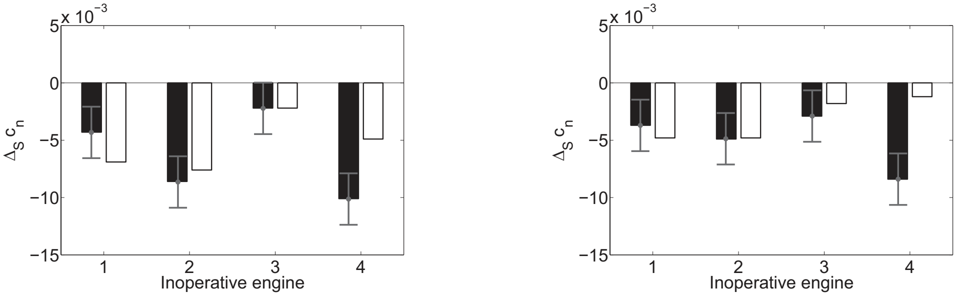
The previous sections described three sources of experimental data useable for validation and three mathematical models. Four different configurations are present in these data sets which are summarized in Table 7.1. The potential model has been compared to all geometries and corresponding results for an extensive validation. The RANS model has not been applied to all configurations as it is not the intention to validate the model, but to use it as a support tool to investigate certain aspects, e.g. the effect of assumptions, of the flow model in more detail.

7.4 Validation

The potential flow model is intended for the evaluation and design of multi-engine propeller aircraft. Since aircraft of this type already exist full scale test data are available[132] and used for validation, raising several questions. Furthermore, the model results are compared to the wind tunnel tests and the RANS model answering some questions but raising even more. Finally the potential and RANS model are compared using the simplified wing–propeller geometry to focus on the source of the differences in lift distribution and resulting side–wash.



(a) $V_\infty = 94$kts (b) $V_\infty = 100$kts



(c) $V_\infty = 106$kts (d) $V_\infty = 124$kts

Figure 7.12: Comparison of the propeller slipstream contribution to the yawing moment, model results and flight test data.

7.4.1 Hercules comparison

The most important results of the comparison between the full scale test and the potential flow model are shown in Figure 7.12. The measurement uncertainty in sideslip angle ± 1 ° results in an yawing moment uncertainty — ± 0.0022 — which is equal in magnitude to the intended propeller slipstream effects[161] as depicted by the confidence intervals in Figure 7.12. Consequently, only an order of magnitude and sign comparison between the model and experimental results is possible.

The potential flow tool provides the correct direction of the effect. However, many questions with respect to the correct mental model are also raised requiring further investigation[132, 161]. In particular, the large difference in predicted and measured propeller slipstream contribution for the two outboard engine inoperative situations requires a more detailed analysis.

This difference in magnitude might be explained by a large sensitivity of the yawing moment and tail side–wash to the proximity of the propeller slipstreams to the vertical tail. Both might be incorrectly predicted by the potential flow model, however the information obtained from this test is too limited to test this hypothesis.

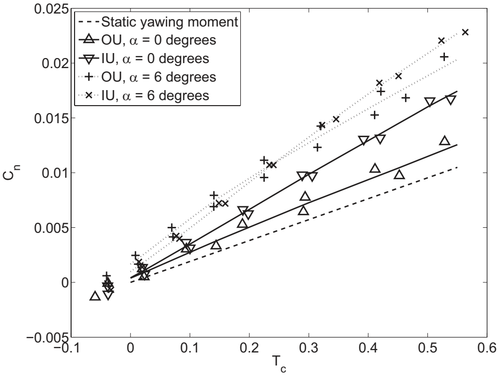


Figure 7.13: Measured thrust versus yawing moment curve for the Fokker F27 configuration with flaps deflected $\delta_f = 24\,^\circ$ at $\alpha = 0\,^\circ$ and $6\,^\circ$.

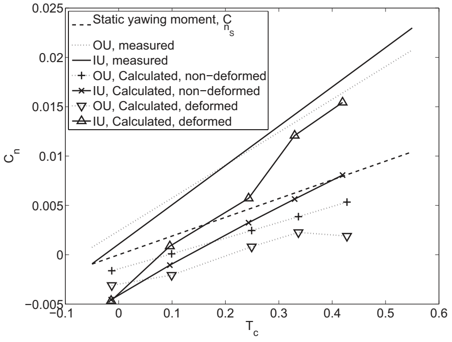


Figure 7.14: Yawing moment coefficient as measured and calculated with the potential model for the Fokker F27 configuration with flaps deflected $\delta_f = 24\,^\circ$ at $\alpha = 6\,^\circ$.

7.4.2 Windtunnel test comparison

To further investigate the cause of the discrepancy between the full scale test and potential flow model, the yawing moments of the dedicated windtunnel tests — Both Fokker F27 and Mannée — are compared to the potential flow model results. In Figure 7.13 the measured yawing moment coefficient versus the thrust coefficient is depicted along with and their least squares approximations. The range of obtained thrust coefficients, from -0.1 to 0.6, is small in comparison with the ones during take-off and employed by Mannée, 0.0 to 2.0, nevertheless, the relative increase in yawing moment is similar to that of larger thrust coefficients. This observation suggests that these measurements are representative and usable for validating the potential flow model.

When both measured and calculated yawing moment coefficients are compared, as visualized in Figure 7.14, the calculated coefficients clearly show an under-estimation. The identification of the source of this discrepancy requires the decomposition and validation of each of the elements.

In order to further investigate the discrepancies, first the components in isolation are verified, using results from the engineering sciences data unit (ESDU) methods as well as measurements performed by Binkhorst[22] in a flow with propellers inoperative.

To validate the model with propeller operative, data obtained from the dedicated measurements and the work of Mannée[107] are used.

Model decomposition

To be able to validate the individual components of the potential flow model, the interactions and component contributions need to be separated. For this purpose it is assumed that the yawing moment coefficient contribution of each aircraft component (indexed i) is assumed to consist of an equivalent side slip angle $\left(\bar{\beta}\right)_i$ and a yawing moment coefficient derivative $\left(C_{n_\beta}\right)_i$,

$$\Delta C_n = \sum_i \left(C_{n_\beta}\right)_i \left(\bar{\beta}\right)_i . \tag{7.5}$$

This requires the implicit assumption, that the effects of a variation in thrust, angle of attack, and propeller rotation direction on the component flow field can be represented as an equivalent side slip angle at the component location. Consequently, this simplification linearizes the interactions and allows for an isolated treatment of the component contributions. The yawing moment coefficient derivatives $\left(C_{n_\beta}\right)_i$ are verified by placing the aircraft without propeller in a uniform flow at a finite angle of side slip without thrust effects. The effects of the propeller on the aircraft are evaluated by comparing the measured and calculated sidewash in front of the vertical tail.

Comparison of the yawing moment derivative

Neglecting the propeller influence for the moment, the aircraft is split into two major components of which the yawing moment coefficient derivatives are determined: the wing-fuselage and the vertical tail. The analysis is done in a uniform flow at a finite angle of side slip and zero angle of attack, with flaps retracted. The measurements performed by Binkhorst[22] as well as ESDU methods[185, 186] are used as reference. The potential flow model results for the yawing moment derivatives were obtained by putting the aircraft at a finite sideslip angle.

Wing-fuselage contribution The left part of Table 7.2, index WF, shows that the yawing moment derivative of the potential model for the wing-fuselage combination agrees well with the measured and computed verification values. The side force derivative, however, is significantly underestimated, which is probably caused by neglecting viscous effects on the front and aft part of the fuselage[117]. Furthermore, the nacelle influence and the fact that the fuselage is approximated by a cylinder, equal in height to the actual fuselage, instead of the actual more elliptic shape are also a cause for errors in fuselage contribution[78]. Moreover, the compensating effect of the wing on the yawing moment derivative was found to be lower than indicated by House and Wallace[78]. Most sources for error are found to be determined by the contribution of the nose of the fuselage at an angle of yaw. The one engine inoperative (OEI) measurements, however, have been performed using zero

Table 7.2: Comparison of the directional stability derivatives, $\alpha = 0\,^\circ$.

	$(C_{n_\beta})_{WF}$	$(C_{Y_\beta})_{WF}$	$(C_{n_\beta})_T$	$(C_{Y_\beta})_T$
Binkhorst [22]	-0.073	-0.1709	0.231	-0.696
ESDU[186]	-0.054	-0.1679	0.289	-0.794
Potential model	-0.092	-0.0736	0.233	-0.629

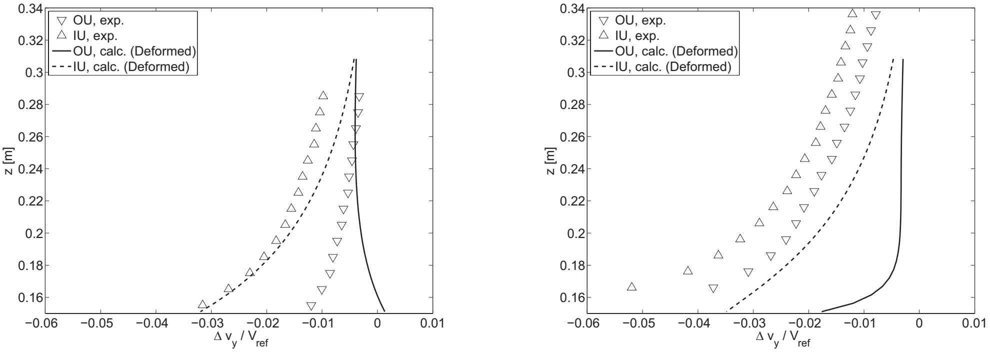
sideslip angle, in which case these sources of error do not occur and the model produces valid results for the contribution of the fuselage-wing combination.
According to Rooyen and Eshelby [155] the contribution of the nacelles is negligible in OEI conditions. This is supported by the potential flow model where the modeled nacelles seem to have a negligible contribution.

Vertical tail contribution The contribution of the vertical tail to the side force and yawing moment derivative is obtained by subtracting the values for wing and fuselage from the total side force and yawing moment derivatives. These values, therefore, include the additional contribution due to the fuselage-fin interaction. The results, shown in the right part of Table 7.2, index T, indicate that the error for the yawing moment derivative is smaller than the ESDU method and well within the range of 10%, generally employed for conceptual design purposes.

Conclusion The previous paragraphs show that the error found in yawing moment for the complete configuration with flaps deflected in one engine inoperative conditions is not caused by the modeling of the components in a uniform flow field at a finite angle of side slip. The cause for difference should, therefore, be sought in an error in calculated sidewash in the situation where the propeller is operating.

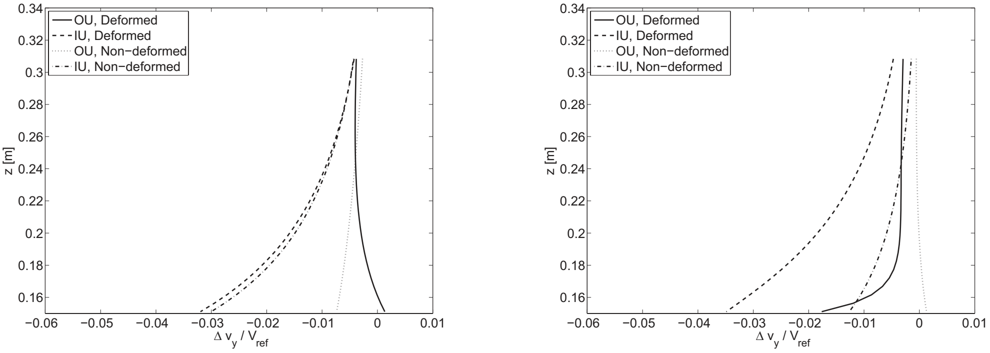
Comparison of the sideslip angle

The second comparison, the sideslip angle, is performed by comparing the five hole probe measurements to the calculated sidewash in front of the vertical tail plane. The vertical tail is chosen as the location of interest as Mannée[107] notes that the additional contribution to the yawing moment is probably caused by the interaction of vertical tail and propeller slipstream. Figures 7.15a and 7.15b, showing the additional sidewash (Δv_y) due to thrust effects, show considerable differences in magnitude as well as trend. Note that the sidewash velocities in the figures include the additional side wash in front of the vertical tail due to the lift production of this tail. The observation that the calculated sidewash for zero angle of attack is larger than the six degrees angle of attack, for inboard up rotation, opposes the measurement results. The calculated side force due to the vertical tail is consequently smaller as well as the resulting additional yawing moment. Further comparison of the calculated results, in particular including wing trailing vortex sheet deformation, does not show the expected difference in sidewash expected from previous work. Further investigation of the vortex sheet shape is therefore required. Mannée[107] attributes this sidewash to the



(a) $\alpha = 0\,^\circ$ (b) $\alpha = 6\,^\circ$

Figure 7.15: Non-dimensional additional sidewash due to propeller installation, at the vertical tail plane, $T_c \approx 0.33$. Side-wash is defined positive in starboard direction.

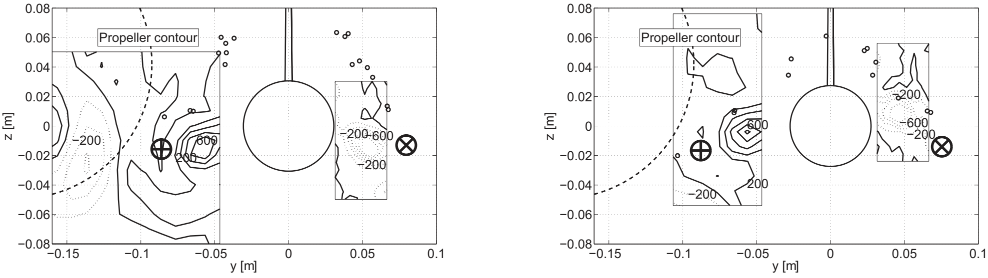


(a) $\alpha = 0\,^\circ$ (b) $\alpha = 6\,^\circ$

Figure 7.16: Effect of wing trailing vortex sheet deformation on the sidewash at the vertical tail plane, $T_c \approx 0.33$.

asymmetrical wing lift distribution. Two contributions are assumed: first, the sidewash due to the *asymmetrical shape* of the vortex field caused by the asymmetrical roll up of the sheet and second, an *asymmetrical vortex strength distribution* of the wing trailing vortex sheet. Both effects are closely related and cannot be seen completely separated. For the potential flow model the effect of shape and strength has been separated by fixing the wing trailing vortex sheet field. The resulting side wash velocities are shown in Figures 7.16a and 7.16b.

The first effect is closely related to the asymmetric movement of the flap tip inner vortex due to the wing trailing vortex sheet and fuselage effect. Previous work[161, 160] suggests that the position of the flap inner vortex has a major contribution to the sidewash at the vertical tail plane. Consequently, this vortex was tracked, in the measurements, along the fuselage at four stations as indicated in Figure 7.4. Figures 7.17a and 7.17b show that the movement of the flap inner vortex for the working propeller side and the propeller inop-



(a) Station 1. (b) Station 4.

Figure 7.17: Measured flap inner vortex position as indicated by contours of constant axial vorticity, at $T_c \approx 0.33, IU, \alpha = 6\,^\circ, IU$. $\oplus$, $\otimes$ and $\circ$ are the calculated port and starboard inner flap tip vortex and additional positions respectively.

erative side is small along the fuselage, for the most critical configuration. Comparing the measurement data to potential model results at both positions (Figure 7.17b) a difference in flap inner vortex position can clearly be seen. Furthermore, there is a large unrealistic contribution of the inboard wing vortices impinging on the vertical tail. The resulting difference in cross flow is therefore probably caused by a discrepancy in lift distribution as well as an effect of dividing the continuous sheet into discrete elements. Subdividing the continuous vortex sheet into singular elements (trailing vortices) provides usable results as long as the positioning of the vortex elements is fixed, can be controlled or disturbances are small. In free wake models the approximation of a continuous vorticity sheet by discrete elements poses a problem when elements are close to each other (collocation points). In order to smoothen the singularities, viscous effects are included by applying a concrete viscous core[181]. These free wake models are only applicable if the distance between the point of interest and the vortex element is larger than 2 times the width of the original vortex element[90]. This condition is satisfied by the vertical tail plane, for the fuselage, on the other hand, this is not trivial. This observation is a likely cause for the discrepancy between the expected inner flap tip vortex position from previous work[161, 160] and currently measured.

The second effect is closely related to the lift distribution on the wing. This can be seen when comparing the sidewash measurements at zero and six degrees angle of attack. Increasing the angle of attack increases the lift and, subsequently, the strength and asymmetry of the wing lift distribution, resulting in a larger sidewash at the vertical tail. In order to investigate a potential difference in lift distribution between the measurements and potential flow model, a simplified computational model has been implemented in the Fluent flow solver. This RANS model was compared to the configuration as measured by Mannée. Figure 7.18 shows an overestimation for both inboard and outboard up rotation, which might be caused by numerical diffusion in the rather coarse grid, which was chosen to limit the computing time. A possible resulting difference in vortical structure on both sides of the fuselage very likely leads to changes in the computed yawing moment coefficient. The trend of the yawing moment, on the other hand, is similar to the measured one, making it still useful for verification purposes.

The comparison of the lift distributions, as computed with the RANS and potential model, in Figure 7.20a shows that the order of magnitude of the results is similar. The negligence

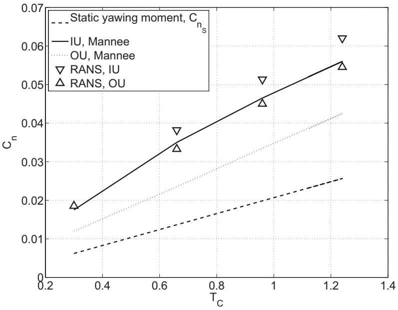


Figure 7.18: The yawing moment coefficient, measurements by Mannée and computations based on the combined RANS model; $\alpha = 5.8\,^\circ$.

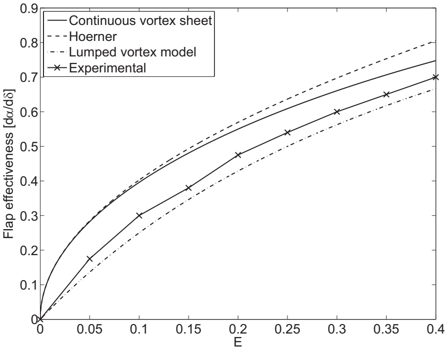
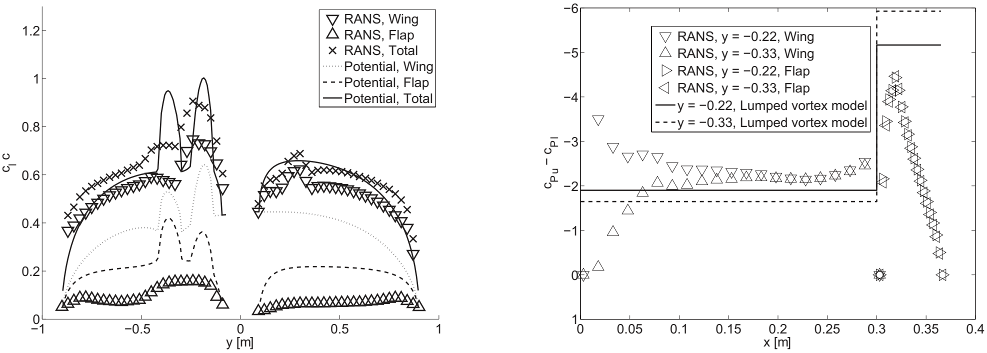


Figure 7.19: Flap effectiveness for various mathematical models and experimental data from Abbot and Doenhoff[1].

of the swirl recovery due to the wing in the potential model, results in the over-estimation of the total lift due to propeller rotation as seen in Figure 7.20. Nonetheless, the potential flow method underestimates the wing lift while it overestimates the flap lift. The fact that the flap carries most of the additional load is due to the basic lifting line model (one vortex element over the wing and one over the flap) as shown in Figure 7.20b. The additional overall load due to the flap deflection[161]

$$\frac{\partial \alpha}{\partial \delta} = \frac{3E}{2E+1}, \tag{7.6}$$

is however comparable to the measurement results obtained by Abbot and von Doenhoff[1, 160]. E is defined as the ratio between the flap chord and total (wing + flap) chord. A comparison of this lumped vortex model with the continuous vortex sheet model[65, 90] and a semi-empirical relation from Hoerner[75] is shown in Figure 7.19. The lumped vortex model can be expected to under predict the lift of the wing with flap deflected, however within the error range provided by the other models. The total wing lift with the contribution of the flap is therefore expected to be similar, and has been verified by adding more horseshoe vortices in chordwise direction. The chordwise distribution of load varied significantly whereas the total load remained fairly similar.



(a) Lift distribution.

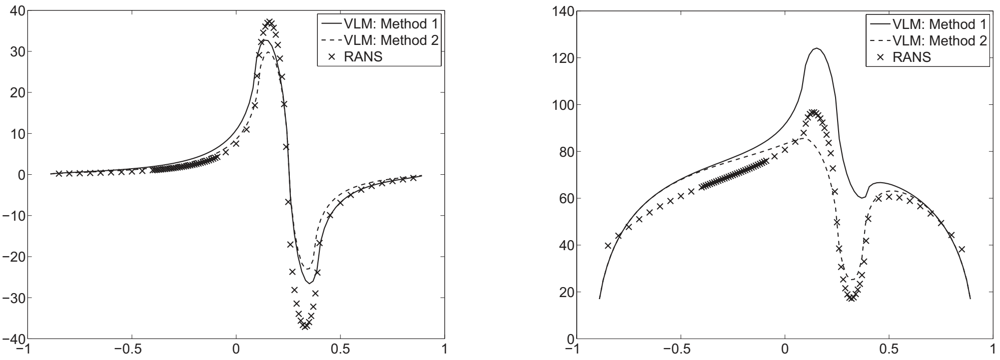
(b) Chordwise pressure coefficient.

Figure 7.20: Results of the RANS model and potential flow method for the configuration as used by Mannée[108]; $\alpha = 5.8\,^{\circ}, T_c = 1.3$, propeller rotating inboard up.

7.4.3 Lift distribution

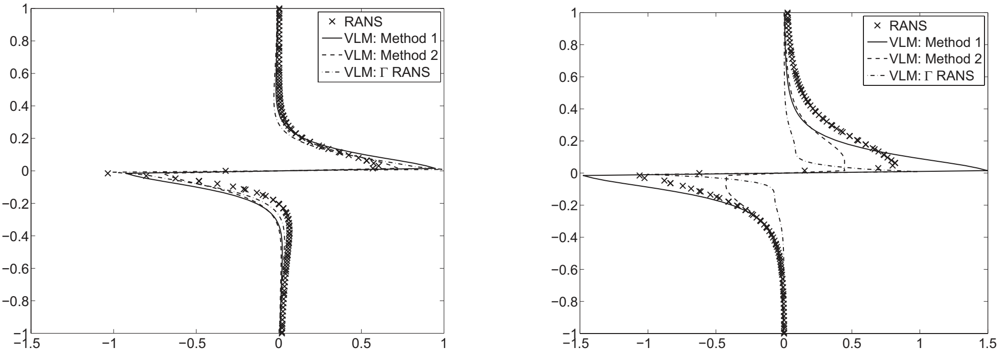
To investigate the differences in potential and RANS results in further detail; the lift distribution on the propeller–wing geometry is used. The lift distribution on the wing is determined by the angle of attack and the local inflow velocity. The geometric inflow angle, angle of attack, is varied between $0\,^{\circ}$ and $5\,^{\circ}$. The uniform velocity field is disturbed by the propeller and produces a change in both section inflow angle and velocity. Two different velocity fields can be adopted to represent the propeller induced velocity field, at the extremes of the spectrum; 1) the propeller induced flow is super imposed on the free stream velocity, and 2) the propeller induced flow introduces a discontinuity in the flow[83]. The lift distributions for the RANS model and both vortex lattice models are given in Figures 7.21. For an angle of attack of $0\,^{\circ}$ the difference lift distribution between models is significant — $\Delta l > 10N/m$ — in the propeller influenced region. This difference is aggravated for the $\alpha = 5\,^{\circ}$ case. Consequently, the current potential model appears unsuitable for the prediction of wing lift distribution for this simplified case. The more difficult case of the wing with flaps deflected, nacelle and fuselage interaction consequently requires further study.

The effect of the difference in lift distribution on the side wash is shown in Figure 7.22. Three situations are investigated; 1) the velocities of the propeller slipstream are superimposed on the flow field, 2) the propeller slipstream is represented as a cylindrical discontinuity in the flow field and 3) the “correct” lift distribution of the RANS simulation is used in the vortex lattice model to determine the side wash. To limit the effect of the vortex sheet roll up as a cause for the difference the location for side wash investigation is located $200mm$ behind the trailing edge of the wing. For the zero lift angle of attack the results are encouraging, i.e. the difference located in a small region near the discontinuous vortex field, located at $z = 0.0$. For the angle of attack of $5\,^{\circ}$ the effect of the various lift distributions can clearly be seen: the agreement of the predicted VLM side wash and RANS side wash is considered unacceptable in all three cases. As a consequence, if the VLM model would be able to correctly predict the lift distribution of the wing, this would not guarantee that the side wash prediction is correct. One possible cause for this might be the slipstream shearing, i.e. the separation of the slipstream due to the presence of



(a) $\alpha = 0\,^\circ$ (b) $\alpha = 5\,^\circ$

Figure 7.21: Lift distributions for the infinitely thin wing.



(a) $\alpha = 0\,^\circ$ (b) $\alpha = 5\,^\circ$

Figure 7.22: Side wash for the infinitely thin wing.

the wing[161]. Predicting the effect of slipstream shearing is considered to be even more complicated for the case of interest, i.e. flaps deflected, large angle of attack and high propeller thrust loading.

7.5 Concluding remarks

Modelling complexity is considered to be represented by the ability of models to represent the real system behaviour, required for the design of the system. Validation is thus required to determine the difference, i.e. error, between model design space representation and the real system design. In this error determination additional information is obtained which supports the design. Furthermore, validation at model level as has been performed in this chapter, i.e. sufficiently accurate, is insufficient in the MDO environment. Errors acceptable at the model level might accumulate in the MDO framework due to the model interconnectedness. To balance the errors at the system level, the tools representing the aspect systems with high sensitivity to the objective function and constraints should be more accurate than the ones with a low sensitivity. In order to fully test model validity in the MDO environment, e.g. BLISS, a single problem should be addressed by a range of different models up to convergence. Consequently, validation should take place at each level, as the validity of component models, e.g. wing model, does not imply validity at the higher levels, e.g. wing-propeller interaction.

Validation of the potential model propeller-wing-tail interaction model has been performed using various sources of information. The usability of the potential model for vertical tail design proposed in this chapter is limited in the conceptual design phase. Further investigation on the correct implementation of the wing lift distribution, propeller slipstream and vortex sheet development is required. This investigation on a seemingly “solved” issue of propeller-wing-tail interaction, shows the difficulty of obtaining trust in a mathematical model in the conceptual design phase. Despite the potential model predictions not directly being usable, the information obtained from the validation of components can be used in the design. In other words, the model itself is only part of the knowledge available to the design team. Consequently, the model is a tool which should represent the knowledge of the design team. From this viewpoint, the creation has led to new insights, which might not be correctly represented by the model, but are part of the knowledge of the design team and can be used in the design.

Focussing on the validation process itself, it has been found that decomposition, e.g. zooming in from the aircraft level to the wing-prop interaction, requires fixing component parameters, e.g. wing geometry and flow properties, to the ones of interest to the current design. This limits the region of validation performed. This is in contrast to MDO which explores a larger part of the (model) design space. This search often enters the regions for which the model has not been validated, which introduces the need for inference from model validity beyond the validated points. For novel configurations the number of validated designs is limited and this inference has a larger effect.

Chapter 8. Coandă Micro aerial vehicle design: M complexity

"To be conscious that you are ignorant is a great step to knowledge."
Benjamin Disraeli.

Modelling complexity is considered to be represented by the ability of models to predict the real system behaviour, required for the design of the system. In this chapter, the belief in model predictions is taken to the extreme by investigating a novel concept for which not much empirical data is available. This in contrast to the previous chapter where the technical solution, i.e. a propeller-aircraft, already is shown to be feasible. The goal of this chapter is therefore to illustrate the probabilistic approach proposed to address modelling complexity. To reduce structural complexity, the seemingly small design problem of a MAV is employed. The MAV is therefore not seen as a solution to the sustainable problem, but the novel technology component is taken as an example. As discussed before, novel technologies are required to achieve the sustainable goals set for aviation. It is therefore important to consider the additional complexities they introduce in the design.

In this chapter a possible implementation of the probabilistic framework, discussed in Section 3.3, addressing modelling complexity. A novel concept, the Coandă vehicle, is used as an example. This is considered a suitable study case since limited information is available on the concept. This prevents "tuning" the inference to the real solution, and allows identification of the (subjective) decisions made by the designer. First a description of the concept is given. From this concept description a single element, the wing, and a single discipline, aerodynamics, is taken to form the feasibility criterion, i.e. vertical lift capability. To test the concept for this feasibility criterion six mathematical models are used to form the input for the previously discussed inference framework.

8.1 Concept description

Current micro aerial vehicles (MAV) perform several functions[8, 163], but are mainly used for various observation tasks. A general mission is shown in Figure 8.1. Consequently,

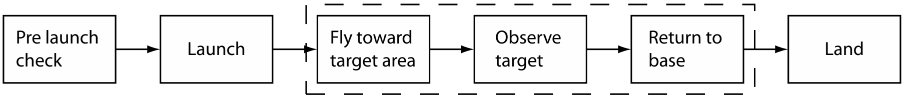


Figure 8.1: Functional flow diagram of the MAV.

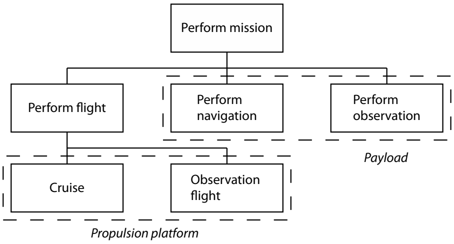


Figure 8.2: Function breakdown structure of the MAV

most MAV consist of a platform carrying an easily interchangeable payload. The platform has received the function of transporting the payload to the desired location and allowing execution of the assigned task as shown in the function breakdown of Figure 8.2. For MAVs several propulsive concepts, i.e. technical solutions, exist: fixed, rotary and flapping wing. Fixed wing aircraft are most efficient on long range missions. Travelling to the observation area is generally efficient, but the lack of hover capability makes single spot observation more difficult. Rotary wing aircraft, on the other hand, have the opposite problem. Single spot observation is efficient but long range flight is less efficient. The third category of flapping wing aircraft are currently limited to small size and employ a complex system of moving parts for propulsion. This is schematically shown in Figure 8.3. Efficient flight over long distances, hover capability and a limited number of moving parts might be achieved by a fourth, new propulsion system based on the vision of Coandă,

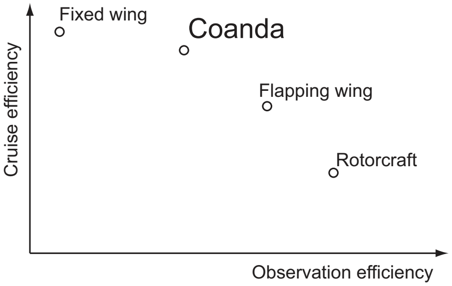


Figure 8.3: Placement of the Coandă MAV in terms of 2 efficiencies.

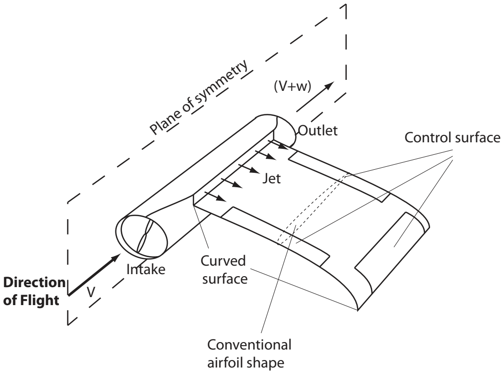


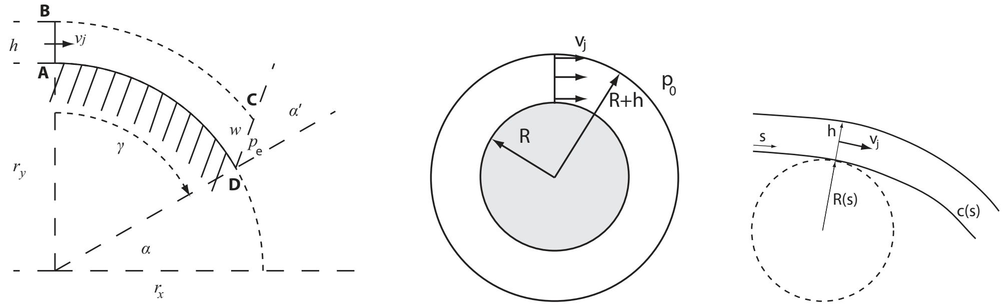
Figure 8.4: Proposed (half) Coandă micro aerial vehicle.

> *"These airplanes we have today are no more than a perfection of a toy made for children to play with. My opinion is we should search for a completely different flying machine, based on other flying principles. I consider the aircraft of the future, that which will take-off vertically, fly as usual and land vertically. This flying machine should have no parts in movement."*

His proposal was to use the Coandă effect to provide a vertical force and consequently hover capability. No successful implementation for manned flight has been achieved so far. Although the Coandă effect has been used to provide short take-off and landing (STOL) capabilities to the Boeing YC-14 aircraft[67]. Furthermore, the Coandă effect has been subject to a lot of investigation to improve extreme STOL characteristics[3]. However, some micro aerial vehicles have been developed [11, 125]. Those vehicles are quite different from the concept proposed here.
The vertical force in hover condition is generated by a jet being curved by a surface from horizontal downward. In cruise flight this surface is also used as a conventional wing to provide lift. The concept discussed in this paper is shown schematically in Figure 8.4. From the two important flight phases identified, cruise and hover, the hover phase is considered in more detail since it is considered the most challenging.

8.2 Feasibility criterion

The hover phase of the MAV is considered to drive the power requirements and the most challenging for the stability and control of the vehicle. In particular, the efficiency of producing the required lift force by the deflection of the jet determines the installed power requirement and consequently the feasibility of the design. Furthermore, vehicle control is proposed by controlling the jet, either directly (thrust setting) or indirectly (deflection angle) to achieve 6-axis control (three rotations and three translations). Since jet control is proposed as the technology to control the vehicle, a close coupling between the controls is expected. Therefore, the behaviour of the jet and how it can be influenced is considered crucial to the design of the Coandă type propulsion platform. As a consequence of this importance, a feasibility estimation of the Coandă effect prediction in hover is considered



(a) Coandă surface. (b) Circular jet. (c) Non circular jet.

Figure 8.5: Control volumes used.

advisable. In mathematical form this is considered to be

$$F_y \geq F_{y,req} \tag{8.1}$$

The required force is, among others, determined by the weight of the concept and the required maneuverability. Neither of these are known, but since the interest lies on the probability of feasibility, consider the criterion to be reformulated as

$$\frac{2F_y}{\rho v_j^2} \geq 0.02 \tag{8.2}$$

as a first estimate. Similar criteria have to be formulated for all considered disciplines and iterated before feasibility of the complete concept can be estimated.

8.3 Mathematical models for assumption-impact evaluation

In order to obtain information on the feasibility criterion, six mathematical models are created from various perspectives on reality, i.e. assumption sets.

Model 1 Addressing the continuity and momentum relations about the control surface shown in Figure 8.5a, assuming inviscid, steady flow without body forces allows for a low fidelity analysis of the effect of the Coandă principle. Writing the conservation of momentum about control volume $ABCDA$ as shown in Figure 8.5a,

$$\oint_{ABCDA} \rho \boldsymbol{v} \cdot \mathrm{d}\boldsymbol{s}\boldsymbol{v} = -\oint_{ABCDA} p\mathrm{d}\boldsymbol{s}. \tag{8.3}$$

Furthermore, assuming constant velocities for the in- and outflow of the control volume, and noting that $BC$and DA are streamlines of the flow results in [4],

$$\int_C^D \rho \boldsymbol{v}(s) \cdot \mathrm{d}\boldsymbol{s} \begin{bmatrix} v_x(s) \\ v_y(s) \end{bmatrix} + \int_A^B \rho v_j \mathrm{d}s \begin{bmatrix} v_j \\ 0 \end{bmatrix} = -\oint p\mathrm{d}\boldsymbol{s}. \tag{8.4}$$

Setting the flow separation angle from the surface at an angle $\tilde{\alpha} = \alpha + \alpha'$, and using continuity of mass, simplifies Equation 8.4 to

$$\rho v_j^2 \frac{h^2}{w} \begin{bmatrix} \sin\tilde{\alpha} \\ -\cos\tilde{\alpha} \end{bmatrix} - \rho v_j h \begin{bmatrix} v_j \\ 0 \end{bmatrix} = -\oint p \mathrm{d}\boldsymbol{s}. \tag{8.5}$$

Evaluating the line integral on the boundary of the control volume for the pressure, defining the normal outward results in

$$\begin{aligned} -\oint p\mathrm{d}\boldsymbol{s} &= p_e \begin{bmatrix} -\sin\tilde{\alpha} \\ \cos\tilde{\alpha} \end{bmatrix} w + p_0 \begin{bmatrix} -h_s - h + w\sin\tilde{\alpha} \\ -l_s - w\cos\tilde{\alpha} \end{bmatrix} + \\ & (p_0 + \Delta p) \begin{bmatrix} h \\ 0 \end{bmatrix} - \int_D^A p(s)\mathrm{d}\boldsymbol{s} \end{aligned} \tag{8.6}$$

evaluating the pressure integral on DA and focusing on the vertical component gives the lift force on the surface,

$$F_y = \rho v_j^2 \frac{h^2}{w} \cos\tilde{\alpha} + (p_e - p_0)\, w \cos\tilde{\alpha}. \tag{8.7}$$

Model 2 An alternative model can be created when considering a steady, continuous jet of circular shape is assumed (Figure 8.5b). Using the Euler equation in radial direction,

$$\rho\left(\frac{\partial u_r}{\partial t} + u_r\frac{\partial u_r}{\partial r} + \frac{u_\theta}{r}\frac{\partial u_r}{\partial \theta} - \frac{u_\theta^2}{r}\right) = -\frac{\partial p}{\partial r}, \tag{8.8}$$

with the appropriate boundary conditions — small segment, pressure forces and centrifugal forces are in equilibrium,

$$\frac{\partial}{\partial t} = u_r = 0, u_\theta = v_j, \tag{8.9}$$

a simplified relation between the pressure gradient and the velocity can be formulated,

$$-\rho\frac{v_j^2}{r} = -\frac{\partial p}{\partial r}. \tag{8.10}$$

This equation states that acceleration of an infinitesimally small element of air along a curved streamline is equal to the pressure gradient. Integrating this equation from the surface (R) to the outer side of the jet ($R + h$), with the free stream pressure known (p_0), results in a constant pressure coefficient on the surface;

$$c_p = -2\ln\frac{R+h}{R} \tag{8.11}$$

in which the jet velocity v_j is used for the dynamic pressure.

Alternative surface shapes might be approximated by their corresponding local circle approximations related through the curvature as shown in Figure 8.5c, consequently assuming the acceleration in flow direction is negligibly small. Given a parametric curve $c(s) = (x(s), y(s))$,

$$\begin{aligned} c_p(s) &= -2\ln\frac{R(s)+h}{R(s)}, R(s) = \frac{1}{\kappa}, \\ \kappa &= \left\| \frac{x'y'' - y'x''}{(x'^2 + y'^2)^{3/2}} \right\| \end{aligned} \tag{8.12}$$

where the primes denote the derivative with respect to s.
Since the interest lies in the force generated on the surface in y direction, this force component is evaluated by multiplying the pressure coefficient with the y component of the surface normal vector,

$$f_y(s) = -\frac{1}{2}\rho v_j^2 c_p(s) n_y = \rho v_j^2 \ln \frac{R(s)+h}{R(s)} \frac{1}{\sqrt{\frac{y'}{x'}^2 + 1}} \tag{8.13}$$

Integrating over the surface curve $c(s)$ gives an equation for the lift force, equivalent to Equation 8.7

$$F_y = \rho v_j^2 \int_c \ln \frac{R(s)+h}{R(s)} \frac{1}{\sqrt{\frac{y'}{x'}^2 + 1}} \mathrm{d}s \tag{8.14}$$

It is assumed that the jet separates from a sharp edge in the surface contour and that the pressure after this sharp edge is equal to the pressure at infinity p_0.

Model 3,4,5 Three different continuous volume models are created and evaluated using the Fluent flow solver [59]. These models are based on the Navier-Stokes [4] equations and assume that the fluid can be represented by a finite number of discrete volumes adhering to continuity properties, i.e. continuity of mass, momentum and energy. This discrete representation is required to solve above equations. Three implementations using different assumptions have been created:

- *Model 3* Euler model, to determine the effect of adverse pressure gradient
- *Model 4* Laminar flow model, $\nu = 1e - 5$, to determine the effect of viscosity (simplified)
- *Model 5* K-epsilon realizable model, $\nu = 1e - 5$, turbulence intensity, surface roughness, to determine the effect of turbulence[165].

All three discrete finite volume models use the same grid and edge boundary conditions. The grid (Figure 8.6) is structured having either 2,550 (GS 1), 10,200 (GS 2) or 40,800 (GS 3) cells to check grid independence. To obtain the effect in the state of interest, the grid is scaled according to the following transformation,

$$\begin{bmatrix} x \\ y \end{bmatrix}_i = \begin{bmatrix} r_x/r_y & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix}_0 \tag{8.15}$$

The solution is considered converged when the equation residuals, x, y–momentum and continuity of mass, are smaller than 1^{-4} and the change in non-dimensional lift coefficient, $2F_y/\rho v_j^2$, is smaller than 1^{-6}. The effect of grid size is checked by a comparison of the solutions obtained on the various grid sizes as shown in Figure 8.7. In particular for the low surface angles, γ the effect of the grid choice on the lift force produced is considerable for all three models. The grid dependency is in the order of 0.01 for $\gamma = 15\,^\circ$. This requires the inclusion of the numerical error in the inference as a cause for uncertainty.

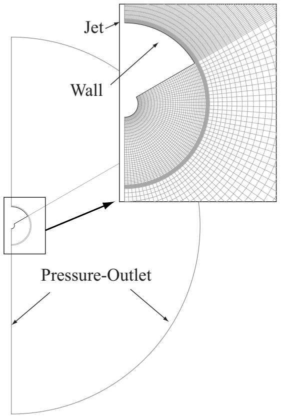
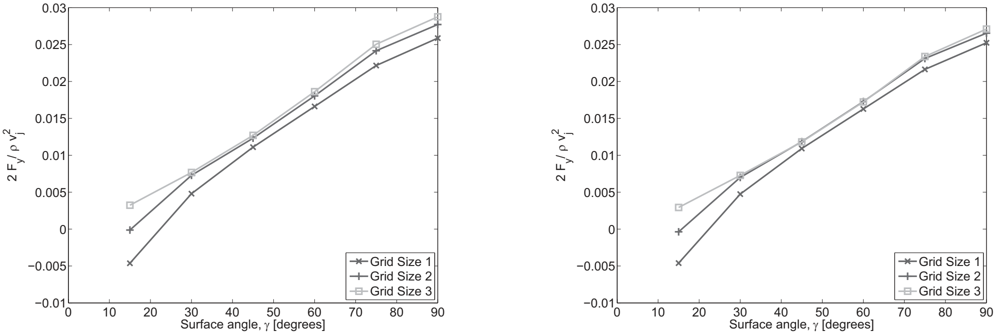
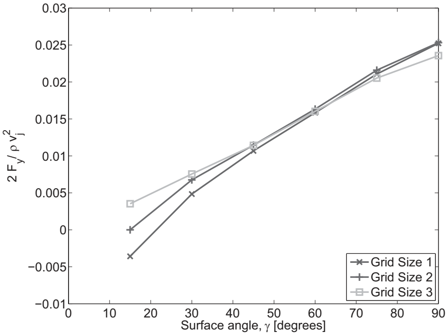


Figure 8.6: Grid employed, $\gamma = 60\,^\circ$, GS 2



(a) Model 4.

(b) Model 5.

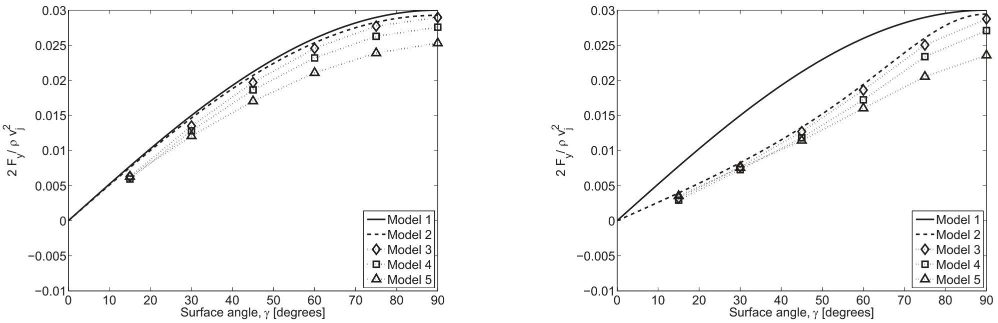


(c) Model 6.

Figure 8.7: Numerical model convergence for $r_x/r_y = 2$.

Table 8.1: Configuration under consideration.

	ν	ρ	v_j	h	$p_e - p_0$	$c(s)$	γ
$\boldsymbol{\xi}$	$1 \cdot 10^{-5}$	1.225	10	0.015	0	$[r_x \sin(\theta), r_y \cos(\theta)]$	$[0, 90]$



(a) $r_x/r_y = 1$

(b) $r_x/r_y = 2$

Figure 8.8: Model predictions for various surface angles γ

Model predictions As a show-case the lift is investigated as defined by Equation 8.2, and its probability on being in range F_{y*}, F_y^*

$$\mathcal{P}(H) = \int_{F_{y*}}^{F_y^*} \varrho(F_y)\mathrm{d}F_y. \tag{8.16}$$

The concept considered is given in Table 8.1. The surface shape $\boldsymbol{c}(s)$ is restricted to a family of ellipsoids, $\boldsymbol{c}(\theta) = (r_x \sin\theta, r_y \cos\theta)$ with $\theta = [0, \alpha]$. The geometric variables are defined as shown in Figure 8.5a.

Figure 8.8 shows the effect of the various assumption sets — both assumed dependencies and their implementation – on the predicted model response. In particular the curvature effect represented by the difference in model 1 and model 2 shows a large difference in predicted force. This is aggravated for large surface angle by the viscosity effect, represented by the difference in model 3,4 and 5. Depending on the trust attributed to each of the models potentially different conclusions can be reached on the feasibility of the concept. The results presented in Figure 8.8 only allow for an acceptance of the feasibility or a rejection depending on the choice of model. The effect of the model errors on the inference and resulting trust in feasibility of the concept is discussed in the next section.

8.4 Inference

The assumed dependencies between concept description variables directly influence the Bayesian belief network structure. For the situation currently under investigation, the probability on a certain force F_y is given by

$$\varrho(F_y) = \int_{-\infty}^{\infty} \varrho(F_y|v_j \cap h \cap p_0 \cap ...)\varrho(v_j)\varrho(h)...\mathrm{d}v_j... \tag{8.17}$$

which states that the force is the dependent variable affected by all variables considered. However, it is assumed that all variables are independent from each other to use the probabilistic framework. This probability distribution is to be evaluated using results from models 1 to 5. The model predicts the actual response $r = F_y$ with a model response m_1 which differs by the uncertain model from error ϵ_m. If the model error is known, a Monte Carlo (MC) simulation for the independent variables, e.g. v_j, h and p_0, would be sufficient to determine the force probability density function. This MC simulation provides insight in the probability on the vertical force, fully determined by the probability of being able to produce a certain design.

First assume that the designer has complete control over the independent variables, i.e. $\varrho(v_j) = \mathcal{N}(v_j, 0)$. If model 1 predicts the real behaviour r without error, a simple observation of the model results, shown in Figure 8.8, suffices to conclude that for any angle $\gamma > 42\,^\circ$, the concept is feasible. However as stated in Section 3.3, model results are subject to various sources of error, of which the model form error is currently of interest. As a consequence, the probability on the error plays a significant role;

$$\varrho(F_y) = \int_{-\infty}^{\infty} \varrho(m_1 + \epsilon_m|v_j \cap h \cap p_0 \cap ...)\varrho(v_j)\varrho(h)\mathrm{d}v_j... \tag{8.18}$$

where the conditional probability for the deterministic models used here is determined by behaviour on ϵ_m since $\varrho(m|...)$ is a delta function[1]. For probabilistic models both the error and the model itself would influence the distribution. Rewriting in the form of the hypothesis results in

$$\begin{aligned} \mathcal{P}(H) &= \int_{F_{y*}}^{F_y^*} \varrho(F_y)\mathrm{d}F_y \\ &= \int_{F_{y*}-m_1(\boldsymbol{\xi})}^{F_y^*-m_1(\boldsymbol{\xi})} \int_{-\infty}^{\infty} \varrho(\epsilon_{m_1}|v_j \cap h \cap p_0 \cap ...)\varrho(v_j)\varrho(h)\mathrm{d}v_j...\mathrm{d}\epsilon, \end{aligned} \tag{8.19}$$

where the lower bound is given by $F_{y*} = 0.01\rho v_j^2$ and the upper bound by $F_y^* = \infty$ From this equation it is clear that the probability on the hypothesis H being true (concept feasible) is determined by the probability density function of the error and the probability density functions of the independent variables. To quantify this model form error, ϵ_m, the assumptions in each model are investigated. As a first approximation the inference is based on the Gaussian distribution, where the mean and variance are determined by the difference in model prediction as well as the designers belief in the appropriateness of the model in representing the assumption $\mathcal{P}(M_i)$[141],

$$\begin{aligned} \varrho(\epsilon_{m_1(\boldsymbol{\xi})}) &= \mathcal{N}(\mu, \sigma^2) \\ \mu &= \sum_{i=1}^{N} \mathcal{P}(M_i)(m_i - \bar{m}_j) \\ \sigma^2 &= \sum_{i=1}^{N} \mathcal{P}(M_i)(m_i - (\bar{m}_j - \mu))^2. \end{aligned} \tag{8.20}$$

---

[1] $p(m|...) = \mathcal{N}(m, 0)$.

Table 8.2: Probabilities of fulfilling the feasibility criterion $r_x/r_y = 2$.

	γ	30°	45°	60°	90°
	$\mathcal{P}_0$	0.000	1.000	1.000	1.000
$\mathcal{P}(M_i) = 1.0$	$\mathcal{P}_F$	0.000	0.000	0.053	0.998
$\mathcal{P}(M_i) = 0.5$	$\mathcal{P}_F$	0.023	0.206	0.512	0.991
$\mathcal{P}(M_i) = 0.0$	$\mathcal{P}_F$	0.000	1.000	1.000	1.000
Park[141]	$\mathcal{P}_F$	0.000	0.051	0.437	0.999

Table 8.3: Uncertainty in state $\boldsymbol{\xi}$.

	μ	σ
ρ	1.225	0.1
v_j	10	0.1
h	0.015	0.001
$p_e - p_0$	0	0

where $\bar{m}$ is the model value obtained from a previous inference. each implementation is determined by the user and is tailored to match the knowledge and beliefs of the user/ designer i.e. both the distribution chosen as well as the appropriateness of the model $\mathcal{P}(M_i)$ when no measurement data are available. This $\mathcal{P}(M_i)$ is subject to the inference and considerations of error extrapolation as discussed in Section 3.3. The mathematical implementation of this error is therefore based on a subjective basis determined by the perception of the user/ designer. Including the information of all models results in the probabilities as shown in Table 8.2. Due to the inclusion of the error the probabilities have decreased for values above 42° and increased below this value.

The design has previously been considered under perfect control of the designer which is not the case. The Coandă concept as described might not perfectly produce a jet velocity of $v_j = 10$ and the outflow pressure might not represent a fully developed stream $p_e = p_0$. The probabilities on these values might be produced from a feasibility inference on the propulsion system, similar to that employed here. Furthermore, the jet height, h, is subject to manufacturing tolerance and also atmospheric conditions, ρ are variable. In order to include these effects, the probability on achieving the feasibility criterion with an actual design based on the independent variables is introduced by assuming a Gaussian distribution representing the independent variables. The properties of the assumed variables are shown in Table 8.3.

The effect on the feasibility —i.e. probability on whether a certain vertical force will occur — is shown for four surface angles in Figure 8.9b and 8.9dfor full belief in the new model, $\mathcal{P}(M_i) = 1$ and ignorance $\mathcal{P}(M_i) = 0.5$ in Figure 8.9a and 8.9c. The black dotted line represents a the value of interest to which the inference is related, i.e. Equation 8.2. Furthermore, five probability distributions are shown, each accounting for an additional set of assumptions represented by the new model. Taking model 1 as a start, the effects of surface shape, denoted $Shape$, adverse pressure gradient, denoted Δp, viscosity, denoted

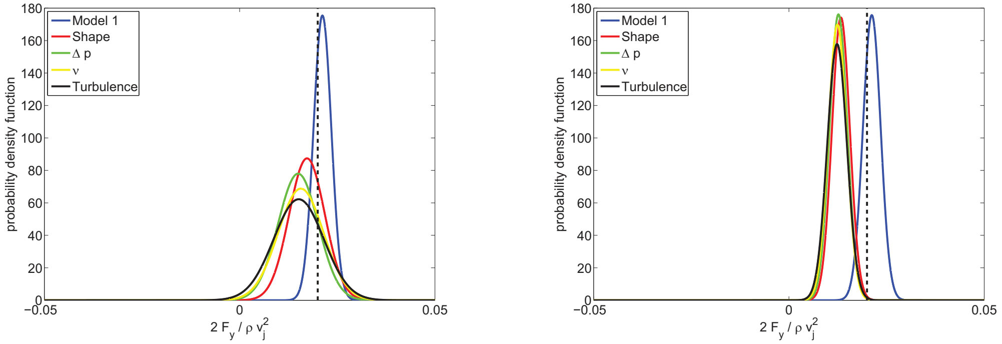
Table 8.4: Resulting probabilities, belief and plausibility of fulfilling the feasibility criterion. $y/x = 2$.

	γ	$30\,^\circ$	$45\,^\circ$	$60\,^\circ$	$90\,^\circ$
	$\mathcal{P}_0$	0.001	0.704	0.984	0.999
$\mathcal{P}(M_i) = 1.0$	$\mathcal{P}_F$	0.000	0.001	0.212	0.923
	$\mathcal{P}_*$	0.000	0.000	0.089	0.388
	$\mathcal{P}^*$	0.580	0.580	0.669	0.968
$\mathcal{P}(M_i) = 0.5$	$\mathcal{P}_F$	0.029	0.224	0.514	0.947
	$\mathcal{P}_*$	0.012	0.094	0.216	0.398
	$\mathcal{P}^*$	0.592	0.674	0.796	0.978

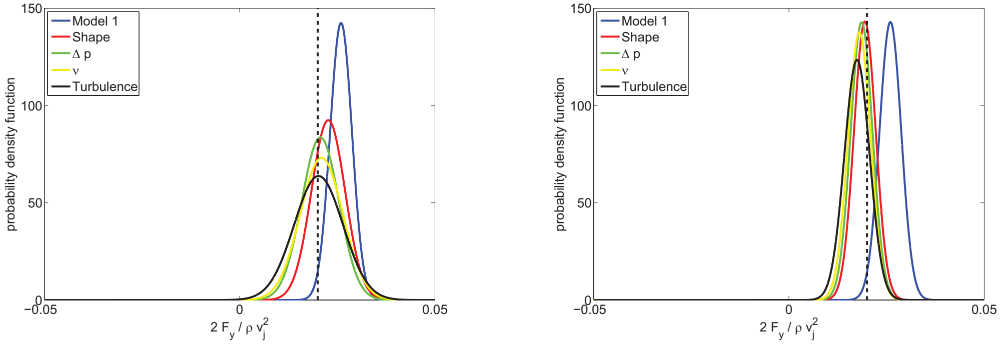
ν and turbulence, denoted $Turbulence$ are included by cumulatively incorporating models $2, 3, 4, 5$ respectively.

The resulting probability distributions of achieving the feasibility criterion value, $2F_y/\rho v_j^2$, for two surface angles considered, clearly show the effect of incorporating the model form error on the probability distribution. The full belief in the new model $\mathcal{P}(M_i) = 1$ results in a shift of the mean value of the distribution with limited effect on the standard deviation. For the ignorance situation $\mathcal{P}(M_i) = 0.5$, the shift of the mean is smaller, but the effect on the standard deviation larger. This is expected as the variance is largely affected by the square of the difference in mean and model value as given by Equation 8.20. The probabilities before (label $\mathcal{P}_0$) and after inference (label $\mathcal{P}_F$) are given in Table 8.4 for two model probabilities $\mathcal{P}(M_i) = [1.0, 0.5]$. The probabilities on achievement are decreased due to the dependence on the lower valued other models. Consequently, introducing the information of the other models using this procedure has decreased the designers “probability” on meeting the feasibility criterion. An alternative representation for both wing geometries $r_x/r_y = [1, 2]$ is given in 8.10. The solid lines represent the mean value as predicted by the inference and the dashed lines represent one standard deviation above and below this mean. Furthermore, Figure 8.10 illustrates that for this example the $\mathcal{P}(M_i) = 0.5$ results in the same mean as the method described in Park[141] for equal model probabilities, $\mathcal{P}(M) = 1/5$. Consequently, both methods are consistent for the chosen probability distribution given by Equation 8.20.

Nevertheless, the set of models and consequently the set of assumptions treated in the inference is limited. As a consequence the set of considered assumptions is incomplete. In order to account for these unconsidered assumptions, Equation 3.31 is employed. The current inference is based on a two dimensional representation of the actual wing. Three dimensional effects are not included which are considered to have a large effect on the achievable force. This information stems from the experience of the designer with for instance conventional wings. Consequently a — arbitrary — value of $\mathcal{P}(F_0) = 0.42$ is used to account for the unconsidered effects. This results in a low belief in the model representing the real world system behaviour. This is the second subjective part — the first is the selection of the model form error distribution — present in this inference. The resulting belief (label $\mathcal{P}_*$) and plausibility (label $\mathcal{P}^*$) is given in Table 8.4.

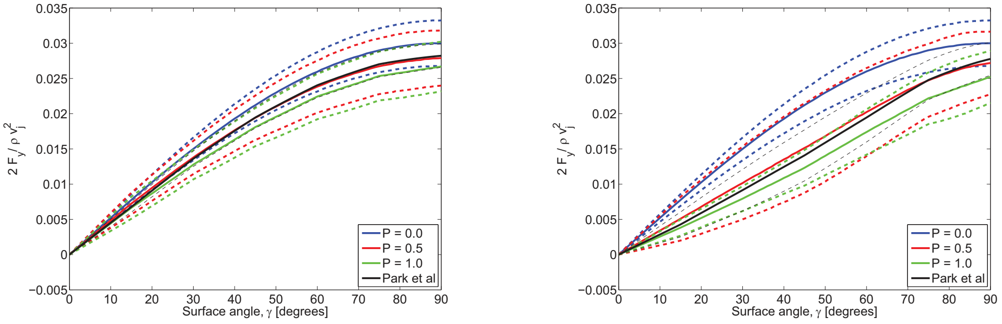


(a) Inference for $\gamma = 45\,^\circ, \mathcal{P}(M_i) = 0.5$. (b) Inference for $\gamma = 45\,^\circ, \mathcal{P}(M_i) = 1.0$.



(c) Inference for $\gamma = 60\,^\circ, \mathcal{P}(M_i) = 0.5$. (d) Inference for $\gamma = 60\,^\circ, \mathcal{P}(M_i) = 1.0$.

Figure 8.9: Effect of incorporating the various assumption corrections and their effects, $y/x = 2$.



(a) Inference for $r_x/r_y = 1$. (b) Inference for $r_x/r_y = 2$.

Figure 8.10: Overall view effect of assumed probabilities.

8.5 Concluding remarks

In order to design novel technologies using computational optimization approaches such as MDO the modelling complexity needs to be addressed. In order to provide insight in the occurrence of modelling complexity for (novel) configurations, the error in model prediction results has been considered. This approach is extrapolated to situations where no comparison with real world behaviour is available. As a consequence uncertainty is introduced in the model design space. This uncertainty is subjective to the user opinion. The user opinion is introduced in two stages in the inference, 1) in the implementation of the probability on a certain error and 2) in the considerations whether the set of assumptions addressed is sufficiently complete. Nevertheless, the various models and their resulting information has been combined in order to come to a structured assessment of the feasibility on the concept. Whether this framework useful in a real design environment remains to be determined. It does provide a framework identifying the unavoidable incompleteness of any inference and allowing the incorporation of the consequent subjective elements in the inference.

Further research should be performed on what entails a correct procedure for the implementation of model error probability distributions. In particular the preference of models is considered an important driver for the assumed distribution. As an example, if the user prefers or trusts one model above the other, the probability distribution is biased towards this models outcomes. Whether this is a correct implementation, or more appropriate means of determining the belief in a certain model can be developed is subject for further study.

Furthermore, the distribution in independent model variables affected by models of different components or aspects of the system. A mutual influence between feasibility criteria is therefore likely to exist. Consequently, the complete modelling structure, as discussed in for instance Chapter 6 should be subject to the interferences. This requires the extension of the framework to multiple dependent feasibility criteria on different aspects of the system, before the feasibility of the overall system can be inferred.

Chapter 9. Conclusions and recommendations

"The system of nature, of which man is a part, tends to be self-balancing, self-adjusting, self-cleansing. Not so with technology."
E.F. Schumacher.

9.1 Conclusions

Aviation is expected to grow and so is its contribution to the anthropogenic impact on the environment. This thesis opens with the statement that the focus on technology improvement is insufficient in the creation of a sustainable aviation system-of-systems. Nevertheless, this improvement does aid in the reduction of anthropogenic impact as long as human behaviour in response to this new technology is accounted for. Therefore, a better approach is to design and evaluate the system, incorporating the sustainable technology, accounting for the human behaviour upfront. This requires the cooperative effort of the true stakeholders as well as an integrated framework to address the issues arising in the prediction of environmental impact. Such a framework enables governments, stakeholders and corporations to predict and evaluate the desirability of a novel technology upfront and should incorporate elements, not only from engineering disciplines, but also social sciences.

The complexity types present in complex adaptive systems such as aviation are taken as a guide to which issues need to be addressed by such a hypothetical framework. These complexities prevent an all at once approach, i.e. a single tool which can address all complexities. Two goals have been formulated to address this problem;

1) *Devise a method that couples system level impact and human/ organizational/ societal behaviour to evaluate the true impact of a technology at the system-of-systems level.*
2) *Investigate the early stages of design to identify the shortcomings of the current design method in reducing the environmental impact and illustrate this using the variety of proposed technical solutions.*

The first goal requires addressing system-of-systems level complexities. In the current context the system-of-systems is aviation, including, but not limited to, airlines, passengers, airports and the communities living near airports. The second goal requires a solution for system level complexities, where system level represents the aircraft system. Four types of complexity have been identified and addressed at appropriate levels by the framework: 1) evaluative, 2) behavioural, 3) structural and 4) modelling complexity.

At the system-of-systems level a method is required to quantitatively incorporate the intertwined stakeholder needs to address the evaluative, behavioural and structural complexity. Quality Function Deployment (QFD) and Value Engineering (VE) provide a good basis for quantifying these effects, i.e. stakeholder behaviour and environmental impact. Also at the system level an integrated approach with respect to the (conceptual) design is required to be able to benefit from the potential synergy. Value Engineering (VE) and Multidisciplinary Design Optimization (MDO) provide a foundation to address the behavioural and structural complexity at the system level. However, the computational MDO approach leans on mathematical representations of real system behaviour. A probabilistic approach is used to estimate the model form error providing a first step in quantifying the modelling complexity.

Three challenges have been formulated for which tools need to be found to address the two aforementioned goals:

1) *Address the complexities at the system-of-systems level. In particular the modelling of stakeholders in a computational domain and the coupling of behaviour, technology and the resulting environmental impact.*
2) *Address the structural and behavioural complexity present in the conceptual design of a system, using a multidisciplinary design optimization framework.*
3) *Address the modelling complexity and in particular the uncertainty in model errors occurring for (novel) technologies.*

This thesis adopts a quantitative approach to address the aforementioned challenges. The first challenge deals with the **system-of-systems** level complexities and the second and third challenge with the **system** level complexities. The integration of the results emanating from these tools is addressed by the previously mentioned QFD, VE and MDO methods. The first challenge was addressed using the Agent Based Modelling and Simulation (ABMS) approach. For the second challenge the Bi-Level Integrated System Synthesis (BLISS) framework was used. Finally the uncertainty in model errors was addressed using Bayes. This has been shown schematically in Figure 9.1.

9.1.1 Agent Based Modelling and Simulation tool

The tool used to solve the first challenge for the integrated stakeholder approach was the Agent Based Modelling and Simulation (ABMS) framework, using economic, game and network theory to address the evaluative, behavioural and structural complexity at the system-of-systems level. This tool treats stakeholders as agents, i.e. elements, in a simulation environment. Each element is characterized by its internal behavioural response. This allows for the easy exchange of agents and/or behaviour resulting in a flexible tool, capable of addressing the changing system-of-systems. These changes of the real system occur in its structure and composition, but also in the insights on how to model agent

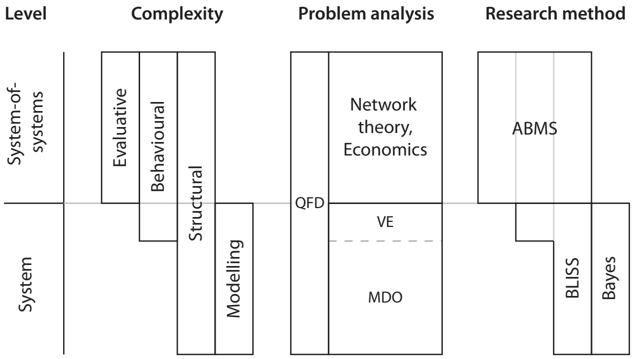


Figure 9.1: Schematic overview of system level, complexity and available and proposed tools addressed in this thesis.

behaviour. For the quantitative behaviour modelling two approaches are considered, 1) direct inference from previous stakeholder behaviour and 2) identification of stakeholder goals and strategies. For the first approach it was found that predictions obtained from methods like discrete choice analysis were limited to previously portrayed stakeholder behaviour. Alternatives like conjoint analysis became resource intensive, due to the large number of attributes characterizing an aircraft. The second approach proved most suitable to address the first challenge and was consequently adopted. The concept of utility is consequently defined as the scalar measure for fulfilment of a stakeholder goal by a strategy, which was selected from the set of strategies available to the stakeholder. Nevertheless, inherent limitations prevented the derived decision models from conclusively predicting future stakeholder behaviour in response to (novel) technologies.

MagLev show case To illustrate the ABMS tool and its ability to address structural and behavioural complexity, the MagLev system technology was taken as a realistic show case. A limited subset of aviation stakeholders and their interactions was used to illustrate the integrated stakeholder approach. The investigated stakeholders consisted of a single airport, community near the airport, five airlines and passengers. Using the agent representations of these stakeholders, three scenarios were investigated to evaluate the environmental impact after introduction of the MagLev system. These scenarios assumed an airport 1) with ample capacity left to satisfy demand, 2) limited capacity left and 3) more demand than capacity available. This airport capacity limit was enforced by a noise sensitive community.

This show case illustrated the reduction of per flight movement environmental impact by the MagLev system, both in terms of noise and carbon dioxide emissions. Despite this reduction at the MagLev system level, the changed airline behaviour negated this reduction in carbon dioxide emissions at the system-of-system level for all three scenarios. However limited this inference, the framework shows that technology impact reduction at the system level does not necessarily reduce system-of-systems environmental impact. Consequently, the sustainable design philosophy of reduction at the system level is proven insufficient. The ABMS treatment provides a first step in the right direction to incorporate the effect of stakeholder behaviour in the prediction of environmental impact.

Prandtl Plane show case The importance of including stakeholder behaviour in the evaluation of technology impact introduces the difficulty of identifying, quantifying and modelling stakeholder behaviour. The Prandtl plane show case illustrates this difficulty for the introduction of novel technologies. In order to address this issue, two changes affecting the behaviour have been considered: changes to the stakeholder strategies and changes to the stakeholder goals. The identification of realistic alternative strategies requires a sufficiently detailed concept, including costs and benefits, to form the basis for communication between manufacturer and stakeholder. Nevertheless, the volatility of stakeholder behaviour only allows identification of small changes in behaviour, which inherently leaves the changes with the largest impact unidentified. Constant revision of the stakeholder models used in the environmental impact evaluation is mandatory. This only elicits the evaluative and behavioural complexity and provides a method, albeit limited, for the quantification of behaviour for stakeholder representation in the ABMS framework. The easily replacable agents allow for the reuse of the ABMS framework while allowing updating agent behaviour when new insights become available.

9.1.2 Bi-Level Integrated System Synthesis

To address the second challenge, the BLISS tool was implemented and used to evaluate a Blended Wing Body (BWB) design. The BLISS framework provided the designer with a tool to analyse the system, composed of (closely) coupled disciplines. Even though the found solution was not feasible due to the too limited design space, the BLISS framework implementation obtained an improved BWB solution, successfully addressing the second challenge.
In particular the (iterative) setup of the problem required designer interference, e.g. the location of the constraint evaluation (blackbox or system level), structuring of the disciplinary model interactions, and considering which models need to be incorporated. Although common to MDO approaches, BLISS facilitated this by the consistent design provided in each iteration. This design consistency allowed the designer to identify bottlenecks using the information provided by the framework like constraint violation, infeasible blackbox optimization or global sensitivity information, in understandable and consistent design space. In each of the iterations designer could stop the optimization obtaining meaningful results. This is a valuable addition in contrast to alternative schemes like “all at once” and “collaborative optimization” which are only consistent if all constraints are satisfied (usually at the optimum).

In addition to the BWB design problem, the BLISS implementation was verified using an analytical problem with a known optimum. Three possible structural implementations, all having a single black box and system optimization, were considered. By linearizing both the objective and constraints it was shown that all three formulations were equivalent, i.e. structure independent, if all constraints were considered in all black box optimizations. However, for a second analytical test case consisting of multiple black box optimizations, this formulation could not be resolved, as all black box optimizations tried and failed to resolve all constraints. Consequently, the structure dependent linearization had to be used.

9.1.3 Bayes

The third challenge was addressed using a probabilistic framework. For this challenge the design problem had been limited to a single discipline, eliminating interdisciplinary structural complexity. The procedure of validation was illustrated using the validation of a potential flow model to support the (conventional) design of multiengine propeller aircraft. When no validation data were available, uncertainty was introduced into the model design space. Error prediction and the uncertainties involved were facilitated using the Bayes probabilistic framework. This tool was illustrated using the novel Coandă vehicle.

Propeller-wing-tail model show case Even though many sources of information were employed to validate the potential flow model, inference beyond this data set remained needed. This was caused by the need of fixing parameters in order to investigate more detailed physical phenomena, when errors were found to be unacceptable. Nevertheless, much more information became available by the process of validation than purely the prediction of values and the determination of the error. In particular the validity of assumptions underlying each of the models was found to be a valuable source of information. For design purposes, where the main focus is to investigate the potential of previously unexplored areas, an estimation of the error and assumption acceptability was necessary.

Coandă vehicle show case The difficulty of identifying the discrepancy between model and reality was evaluated using the unconventional Coandă micro aerial vehicle (MAV). To focus on modelling complexity, the — mono-disciplinary — design of the curved surface of the MAV in hover condition was taken. To quantify the uncertainty in error magnitude a probabilistic approach was used. The inference was applied to six models representing the vertical force generated by the Coandă vehicle. The expected error mean value and standard deviation were shown to depend on the probability of correctness attributed to each of the models and their assumption sets. The inference employed on two geometries, a circle and an ellipse, illustrated that the probability of achieving the feasibility criterion ranged from 0.053 to 1.000 for a surface angle of $60\,^{\circ}$. This feasibility depended heavily on the chosen model assumption validity. However, it was considered that the incorporated model assumptions represented a limited set compared to the real situation. As a consequence, the belief in model prediction was highly reduced to a range of 0.022 to 0.42.

Due to the need of introducing the designers opinion into the inference, no conclusive answer could be given on the design feasibility. However, this method provided a structured approach to estimate the model feasibility, based on the assumptions underlying the models considered. In this estimation, two sources of subjectiveness were identified. The first was introduced in the estimation of the error due to an assumption. In choosing a particular assumption induced error, the user set the preference for a certain model. The second subjectiveness was introduced by the required estimation of model assumption completeness.

9.2 Recommendations

This thesis tried to identify and provide solutions to the sustainable conundrum. One challenge to be overcome is how and which stakeholders should be given influence on the design. In this thesis it has been assumed that the earth carrying capacity is known and quantified and represented by all stakeholders. These assumptions are subject to political and scientific debate and their validity has not been considered in this thesis. However, they determine what is considered "desirable" in this thesis and need further substantiation. Despite the large influence of these issues on the environmental impact, advances in technology can *aid* in the reduction of environmental impact at the system-of-systems level. For more sustainable products this requires an integrated approach, both at the system-of-systems level and at the system level. Consequently, projects aiming at the reduction of environmental impact should at least address these stakeholder interactions and project focus should be broadened from mere technology improvement towards true environmental impact reduction incorporating the needs of the *true* stakeholders.

Technology improvement requires a prediction of stakeholder behaviour, which is one of the most challenging elements. This research has only focussed on how technology changes the behaviour of stakeholders. Limited effort has been put in the question of how the behaviour can be changed (by technology or otherwise) to limit anthropogenic impact. That is: can behaviour be changed using technology to stimulate decisions in the group interest instead of individual interest and as such efficiently steer technology towards the needs of a sustainable society. The current predictive capability has to be extended to not only predict the environmental impact, but also "design the environment" in which the technology operates. As a basis for this Method Design could be used in extension to the currently used game-theoretic predictions of stakeholder behaviour. The ABMS approach can still be used to support the prediction of environmental impact effects caused by deliberate changes in the environment.

As a first improvement for a sustainable human society, it was proposed that all product developments should include upfront evaluations of the desirability of the development of the product. This evaluation of the desirability has to account for the stakeholder behaviour and stakeholder interactions and should replace the "find a market for the product" criterion. However, this preemptive check on product desirability hampers innovation as most technologies cannot be shown to comply due to a lack of information. This lack of information should not prevent innovation but requires constant re-evaluation of its desirability. As a consequence, the reversibility of a technology, that is the amount of effort required to revert its impact, needs to be considered as well. Appropriate means to incorporate the reversibility costs in the technology desirability evaluation need further study in line with risk analysis.

Although the search for a generic and all-at-once tool is futile due to the complexity present in real world problems, the study of the elements and their interactions is still necessary. The tools proposed in this thesis provide a complete framework, however they are still loosely coupled. QFD provides the glue between their results, but this bond needs to be reinforced. A more thorough study is required on how the three proposed tools interact and how their predictions can be applied to improve product design. In particular the complementary views provided by the tools can contribute to the "design for sustainability" and arrive at a sustainable future for aviation. Future research should be focussed on the interaction of the various tools and how they can be improved to better support design for sustainability using A real design process, including all stakeholders, their interactions as well as the complexities of designing a product. This will be the true test of the set of tools and their ability to improve product sustainability.

System-of-systems level

At the system-of-systems level three complexities were treated; evaluative, behavioural and structural. The QFD framework addressed the evaluative complexity, together with the VE framework. The evaluation of these methods has been limited to the elicitation and incorporation of stakeholder requirements in the design. This should be elaborated to incorporate the effects of various designs on the needs of the stakeholders. These approaches should be investigated in an actual design environment to investigate their implications on the product design. An actual design environment drastically increases the number of variables required to describe the product, the stakeholders and their interactions. The number of variables is likely to prevent the simulation from being run on a conventional computer and puts additional requirements on the implementation and usability of the ABMS tool.

The additional challenge posed by the incorporation of human behaviour in the simulation is its volatility. Historically, the human mind has shown to be very flexible in finding solutions to large problems. The research effort should therefore not be in the correct mathematical representation and prediction of stakeholder behaviour in the simulation. This should be addressed by continuous updating of the behavioural models, using the flexible nature of ABMS to quickly interchange behavioural models. The focus should lie on how the improved understanding of interacting stakeholders for "given" behaviour affects technology environmental impact. Furthermore, to support Method Design, design changes are to be considered in relation to environment changes. This simultaneous design of the technology and its environment deserves additional research.

System level

At the system level three complexities were treated; behavioural, structural and modelling. The first two were addressed using the BLISS framework. The BLISS framework showed that structural complexity could be managed, and solutions were found in the model design space. Nevertheless, a limited number of disciplinary models, i.e. aspect systems, have been considered for a BWB. This number should be increased to make a fair comparison with the conventional type aircraft. Examples of additional disciplines might include economics, maintenance and control and stability. Finally, the framework has only been evaluated in a "controlled environment"; a real design environment poses different challenges to the framework. As an example consider the transfer of information between disciplines in the system analysis phase within a company setting, or even between manufacturer and subcontractors.

The modelling complexity has been addressed using a probabilistic framework to illustrate the uncertainty present in any design. In particular in the MDO framework a discrepancy might exist between the real design space and the design space represented by the set of disciplinary models considered. This has been illustrated by the — well known — mono-disciplinary propeller-wing-tail aerodynamic interaction modelling. The discrepancies in model and real design should be investigated in more detail by windtunnel tests on various configurations. These tests should broaden the understanding of the interaction effects, instead of focussing on understanding all phenomena on a single configuration.

To investigate the modelling complexity for novel concepts, the Coandă vehicle was used. Again, the treatment of the Coandă vehicle show case was limited to a mono-disciplinary design. The uncertainties were still based on model results, to investigate the feasibility of these estimates, the Coandă show case should be extended by performing measurements on an actual wing design. The current treatment of uncertainty in model prediction error should be extended to a multidisciplinary environment, to provide a useable framework for the conceptual design phase. As an example: model sensitivity for input error introduces error propagation (damping or enforcement of errors) between models and consequently uncertainty propagation. To predict feasibility of a concept this propagation should be addressed before usable evaluations can be performed.

Bibliography

[1] I.H. Abbot and A.E. von Doenhoff. *Theory of wing sections*. Dover publications inc., 2nd edition, 1959.

[2] Boeing Commercial Airplines. Boeing future outlook 2009-2029, 2009. www.boeing.com/commercial/cmo, consulted 2010.

[3] N.R. Alley, J. Steele, J.C. Neidhoefer, R.J. Englar, and G. Blaylock. Development of a cruise-efficient extreme stol capable demonstrator UAV. In *AIAA Infotech aerospace 2010 20–22 April 2010, Atlanta Georgia*, number 2010-3450 in AIAA, 2010.

[4] J.D. Anderson, Jr. *Fundamentals of aerodynamics*. McGraw Hill, second edition, 1991.

[5] Anonymous. *VSAero, A code for calculating nonlinear aerodynamic characteristics of arbitrary configurations, User's manual Version 7.1*. Analytical methods, Inc., Redmond, Washington, U.S.A., 2005.

[6] N.E. Antoine and I.M. Kroo. Aircraft optimization for minimal environmental impact. *Journal of aircraft*, Volume 41, Number 4:790–797, 2004.

[7] L. Argote and D. Epple. Learning curves in manufacturing. *Science*, Volume 247:920–924, 1990.

[8] R. Austin. *Unmanned aircraft systems: UAVs Design, development and deployment*. AIAA Education Series. Wiley and Sons, 2010.

[9] A. Bandura. *Social foundations of thought and action: a social cognitive theory*. Englewood Cliff, New Jersey, Prentice-Hall, 1986.

[10] A.L. Barabasi and R. Albert. Emergence of scaling in random networks. *Science*, Volume 286:509–512, 1999.

[11] C. Barlow, D. Lewis, S.D. Prior, S.Odedra, M. Erbil, M. Karamanoglu, and R. Collins. Investigating the use of the coanda effect to create novel unmanned aerial vehicles. In *International Conference on Manufacturing and Engineering Systems Proceedings*, number ISSN 2152-1522, pages 386–391, 2009.

[12] A.A. Bartlett. Reflections on sustainability, population growth and the environment. *Population and environment*, Volume 16:5–35, 1994.

[13] T. Bayes. An essay towards solving a problem in the doctrine of chances. *Philosophical transactions of the royal society*, Volume 53:370–418, 1763. Reprinted in

Biometrika Volume 45:293–315, 1958.

[14] G. Bekebrede. *Experiencing complexity: a gaming approach for understanding infrastructure systems*. PhD thesis, Delft University of Technology, Delft, 2010.

[15] R.E. Bellman and S.E. Dreyfus. *Applied dynamic programming*. Princeton university press, 1962.

[16] P.P. Belobaba. *Air travel demand and airline seat inventory management*. PhD thesis, Massachusetts Institute of Technology, 1982.

[17] M. Ben-akiva and S. Lerman. *Discrete Choice Analysis: Theory And Application To Travel Demand*. MIT Press, 1985.

[18] C.L. Benkard. A dynamic analysis of the market for wide-bodied commercial aircraft. *Review of economic studies*, Volume 71:581–611, 2004.

[19] J. Bentham. *An introduction to the Principles of Morals and Legislation*. Batoche books, 1781.

[20] A. Betz. Behavior of vortex systems. Technical Report TM-0713, NACA, 1932.

[21] H.G. Beyer and B. Sendhoff. Robust optimization - a comprehensive study. *Computer methods in applied mechanics and engineering*, Volume 196:3190–3218, 2007.

[22] H. Binkhorst. Windtunnelmetingen aan een model van de fokker f-27 “friendship” in de lage-snelheidstunnel van de onderafdeling vliegtuigbouwkunde. Technical Report M-47, Technische Hogeschool Delft, Delft, 1961.

[23] B.S. Blanchard and W.J. Fabrycky. *Systems engineering and analysis*. Prentice Hall, third edition, 1998.

[24] T.C. Botimer and P.P. Belobaba. Airline pricing and fare product differentiation: A new theoretical framework. *Journal of the operational research society*, 1999.

[25] P. Brooker. Civil aircraft design priorities: air quality? climate change? noise? *The Aeronautical Journal*, Volume 110(2995):517–532, 2006.

[26] T.R. Browning. Applying the design structure matrix to system decomposition and integration problems: a review and new directions. *IEEE Transactions on Engineering Management*, Volume 48, Number 3:292–306, 2001.

[27] Brundtland, editor. *Our common future: the world commission on environment and development*. Oxford University Press, 1987.

[28] R. Buchanan and V. Margolin, editors. *Discovering Design: explorations in design studies*. The University of Chicago press, 1995.

[29] K.J. Button. A simple analysis of the rent seeking of airlines, airports and politicians. *Transport Policy*, Volume 12, Number 1:47–56, 2005.

[30] I.J. Chen, A. Gupta, and W. Rom. A study of price and quality in service operations. *International Journal of Service*, Volume 5(2):23–33, 1993.

[31] M.R. Chertow. The IPAT equation and environmental impact. *Journal of industrial ecology*, Volume 4, Number 4:13–29, 2001.

[32] C.M. Christensen. *The Innovators Dilemma: When New Technologies Cause Great Firms to Fail*. Harvard Business School Press, 2000.

[33] J.P. Clark. *Buying the big jets*. Ashgate, 2001.

[34] J.E. Cohen. Population growth and earth's human carrying capacity. *Science*, Volume 269:341–346, 1995.

[35] L. Cohen. *Quality function deployment: how to make QFD work for you*. Addison-Wesley, 1995.

[36] Airbus Company. Global market forecast 2009-2028, 2009. www.airbus.com/en/corporate/gmf2009, consulted 2010.

[37] L.W. Crum. *Value engineering: the organised search for value*. Longman, UK, 1971.

[38] R. Curran, T. Abu-Kias, M.J.F. Repco, Y.L.J. Sprengers, P.N.C.S. van der Zwet, and W. Beelearts. A value operations methodology for value driven design: medium range passenger airliner validation. In *48th AIAA aerospace sciences meeting including the new horizons forum and aerospace exposition, 4-7 January 2010, Orlando, Florida*, number 2010-0847 in AIAA, 2010.

[39] R. Curran, S. Raghunathan, and M. Price. Review of aerospace engineering cost modelling: the genetic causal approach. *Progress in aerospace sciences*, Volume 40:487–534, 2004.

[40] Giulio D'Agostini. Probability and measurement uncertainty in physics - a bayesian primer, December 1995. Available from: http://xxx.lanl.gov/abs/hep-ph/9512295v2.

[41] D. DeLaurentis. Understanding transportation as system of systems design problem. In *AIAA Aerospace Sciences Meeting and Exhibit 10-13 January, Reno Nevada*, number 2005-0123 in AIAA, 2005.

[42] D. DeLaurentis and R.K. Callaway. A system-of-systems perspective for public policy decisions. *Review of Policy Research*, Volume 21, Number 6:829–837, 2004.

[43] D. DeLaurentis, E.-P. Han, and T. Kotegawa. Network-theoretic approach for analyzing connectivity in air transportation networks. *AIAA Journal of Aircraft*, Volume 45, Number 5:1669–1679, 2008.

[44] A.V. DeMiguel and W. Murray. An analysis of collaborative optimization methods. In *8th AIAA/USAF/NASA/ISSMO symposium on multidisciplinary analysis and optimization 6-8 September 2000, Long Beach, CA*, number 2000-4720 in AIAA, 2000.

[45] R. Denos and G. Paniagua, editors. *Aero-engine design: from state-of-the-art turbofans towards innovative architectures*. Von Karman Institute, 2008.

[46] R. Doganis. *The airport business*. Routledge, 1992.

[47] R. Doganis. *Flying off course*. Routledge, second edition, 2001.

[48] R. Doganis. *The airline business in the 21st century*. Routledge, 2003.

[49] G.L. Donohue. Air transportation is a complex adaptive system: not an aircraft design. In *AIAA/ICAS International Air and Space Symposium and Exposition: the next 100 year, 14–17 July 2003, Dayton, Ohio*, number 2003-2668 in AIAA, 2003.

[50] M. Drela and H. Youngren. *XFOIL 6.9 User Primer*, 2001.

[51] W.F. Durand, editor. *Aerodynamic theory*, volume IV, K-N. Springer, 1935.

[52] R.G. Easterling. Measuring the predictive capability of computational models. *SAND 2001-0243*, 2001.

[53] EEA. Annual european community greenhouse gas inventory 1990–2006 and inventory report 2008. Technical Report Technical report No 6/2008, European Environment Agency, 2008. www.eea.europa.eu/publications/technical_report_2008_6.

[54] Ehrlich and Holdren. Impact of population growth. *Science*, Volume 171:1212–1217, 1971.

[55] M.E. Eshelby. The influence of running propellers on low speed longitudinal static stability trim curves. Technical Report Aero Report 34, Cranfield institute of technology, Cranfield, 1977.

[56] J. Rockstrom et al. Planetary boundaries. *Ecology and society*, Volume 14, Number 2, 2009.

[57] J. Rockstrom et al. A safe operating space for humanity. *Nature*, Volume 461:472–475, 2009. doi: 10.1038/461472a.

[58] FAA. Integrated Noise Model, (INM).

[59] Inc. Fluent. Fluent 6.3. user's guide. Manual, ANSYS, Fluent Inc., Lebanon, NH, 2006.

[60] P. Galison. *How experiments end*. The university of Chicago press, 1987.

[61] B.J. Gamble and M.F. Reeder. Experimental analysis of propeller-wing interactions for a micro air vehicle. *Journal of aircraft*, Volume 46, Number 1:65–73, 2009.

[62] G.Booch. *Object oriented design with applications*. Reading mass: Addison-Wesley, Second edition, 1993.

[63] J.P. Giesing. Lifting surface theory for wing-fuselage combinations. Technical Report DAC-67212, Douglas Aircraft company, 1968.

[64] D.A.J. van Ginneken, M. Voskuijl, M.J.L. van Tooren, and A. Frediani. Automated control surface design and sizing for the prandtl plane. In *6th AIAA Multidisciplinary Design Optimization Specialist Conference, Orlando, Florida*, number 2010-3060 in AIAA, 2010.

[65] H. Glauert. *The elements of aerofoil and airscrew theory*. Cambridge University Press, Cambridge, second edition edition, 1947.

[66] S.D. Green. Beyond value engineering: smart value management for building projects. *International Journal of Project Management*, Volume 12(1):Pages 49–56, 1994.

[67] C.A. Grotz. Development of the YC-14 propulsion system. In *American Institute of Aeronautics and Astronautics and Society of Automotive Engineers, Propulsion Conference, 11th, Anaheim, Calif., Sept 29-Oct 1*, number 1975-1314 in AIAA, 1975.

[68] S. Gunawan and P.Y. Papalambros. A bayesian approach to reliability-based opti-

mization with incomplete information. *Journal of mechanical design*, Vol. 128:Pages 909–918, July 2006. DOI: 10.1115/1.2204969.

[69] E. Han and D.A. DeLaurentis. A network theory-based approach for modelling a system-of-systems. In *11th AIAA/ISSMO Multidisciplinary Analysis and Optimization conference, 6-8 september, Portsmouth Virginia*, number 2006-6989 in AIAA, 2006.

[70] Hardin. Tragedy of the commons. *Science*, Volume 162:Pages 1243–1248, 1968.

[71] G.A. Hazelrigg. *Systems engineering: an approach to information-based design*. Prentice Hall, 1996.

[72] G.A. Hazelrigg. Validation of engineering design alternative selection methods. *Engineering Optimization*, Volume 35:103–120, 2003.

[73] T. Hendrich. Multidisciplinary design optimization of the blended wing-body. Master's thesis, Delft Univeristy of Technology, 2011.

[74] E. van Hinte and M.J.L. van Tooren. *First read this*. 010, 2008.

[75] S.F. Hoerner. *Fluid-dynamic lift: Practical information on aerodynamic and hydrodynamic lift*. Hoerner Fluid Dynamics, 2nd edition, 1992.

[76] J.H. Holland. *Hidden order; how adaptation builds complexity*. Reading: Addison-Wesley, 1995.

[77] S. Holloway. *Straight and level: practical airline economics*. Ashgate, 2nd edition, 2007.

[78] R.O. House and A.R. Wallace. Wind-tunnel investigation of effect of interference on lateral-stability characteristics of four naca 23012 wings, an elliptical and a circular fuselage and vertical fins. Technical Report R-0705, NACA, 1941.

[79] ICAO. *Doc 8168, PANS-OPS Volume I; Aircraft operations, flight procedures*. ICAO, 5th edition edition, 2006.

[80] ICAO. ICAO engine exhaust emissions databank, 2007.

[81] D.A. Irwin and N. Pavcnik. Airbus versus Boeing revisisted: international competition in the aircraft market. *Journal of international economics*, Volume 64:Pages 223–245, 2004.

[82] W.A. Jacobs. Magnetic launch assist: Nasa's vision for the future. Technical report, NASA, 2000. note: http://ntrs.nasa.gov.

[83] A. Jameson. The analysis of propeller–wing flow interaction. In *Analytic Methods in Aircraft Aerodynamics*, number SP–228 in NASA, pages 721–749. NASA Symposium Proceedings, 1969.

[84] M. Janic. Aviation and externalities: the accomplishments and problems. *Transportation Research Part D*, Volume 4:159–180, 1999.

[85] M. Janic. Methodology for assessing sustainability of an air transport system. *Journal of air transportation*, Volume 7(2):115–152, 2002.

[86] M. Janic. Modelling operational, economic and environmental performance of an air transport network. *Transportation Research Part D*, Volume 8:415–432, 2003.

[87] M. Janic. Sustainable transport in the european union: a review of the past research and future ideas. *Transport Reviews*, Volume 26, Number 1:81–104, 2006.

[88] P.W. Jansen, R.E. Perez, and J.R.R.A. Martins. Aerostructural optimization of non-planar lifting surfaces. *Journal of Aircraft*, Volume 47, Number 5:1490–1503, 2010.

[89] X. Jiang and S. Mahadevan. Bayesian inference method for model validation and confidence extrapolation. *Journal of applied statistics*, Volume 36, Number 6:659–677, June 2009.

[90] J. Katz and A. Plotkin. *Low speed aerodynamics*. Cambridge University Press, Cambridge, 2nd edition, 2001.

[91] S. Katzoff. Longitudinal stability and control with special reference to slipstream effects. Technical Report R-690, NACA, 1940.

[92] M.C. Kennedy and A. O'Hagan. Bayesian calibration of computer models. *Journal of the Royal Statistical Society*, Volume 63, Part 3:425–464, 2001.

[93] G. Klepper. Entry into the market for large transport aircraft. *European economic review*, Volume 34:Pages 775–803, 1990.

[94] Kodiyalam and J. Sobieszczanski-Sobieski. Multidisciplinary design optimization, some formal methods, framework requirements, and application to vehicle design. *International journal of vehicle design*, Volume 25(1–2), 2001.

[95] H. Kok. Quantitative assessment of a distributed propulsion system featuring boundary layer ingestion turbofan engines applied to a blended wing body aircraft. Master's thesis, Delft University of Technology, 2008.

[96] R. Krasny. Computation of vortex sheet roll-up in the trefftz plane. *Journal of Fluid mechanics*, Volume 184:123–155, 1987.

[97] S. Kroonenberg. *De menselijke maat: de aarde over tienduizend jaar*. Atlas, 2nd edition, 2008.

[98] J.R. Kuhn and J.F. Courtney et al. Agent based analysis and simulation of the consumer airline market share for frontier airlines. *Knowledge based systems*, Volume 23:875–882, 2010.

[99] J.P Kuiper. Unconventional take-off and landing methods for CleanEra. Master's thesis, Delft Univeristy of Technology, 2009.

[100] A. Kumar and J. Hefner. Future challenges and opportunities in aerodynamics. In *22nd Congress of the International Council of the Aeronautical Sciences*, ICAS, 2000.

[101] G. LaRocca. *Knowledge based engineering techniques to support aircraft design and optimization*. PhD thesis, Delft University of Technology, 2011.

[102] P.J. Lederer and R.S. Nambimadom. Airline network design. *Operations Research*, Volume 46(6):785–804, 1998.

[103] S.D. Levitt and S.J. Dubner. *Freakonomics: a rogue economist explores the hidden side of everything*. William Morrow, 2005.

[104] R. Liebeck. Design of the blended wing body subsonic transport. *Journal of Aircraft*,

Volume 41, Number 1, 2004. doi: 10.2514/1.9084.

[105] R.D. Luce and H. Raiffa. *Games and decisions: introduction and critical survey*. Unabridged Dover, 1989. Republication of 1957 edition published by John Wiley and Sons.

[106] S. Mahadevan and R. Rebba. Inclusion of model errors in reliability-based optimization. *Transactions of the ASME*, Vol. 128:Pages 936–944, July 2006. DOI: 10.1115/1.2204973.

[107] J. Mannée. Windtunnel investigation of the influence of the aircraft configuration on the yawing- and rolling moments of a twin-engined propeller driven aircraft with one engine inoperative. Technical Report NLL A-1508 B, Nederlands Luchtvaart Laboratorium, Amsterdam, 1962.

[108] J. Mannée. Windtunnel onderzoek naar de invloed van de vliegtuigconfiguratie op gier- en rolmoment ten gevolge van het uitvallen van een motor bij een tweemotorig schroefvliegtuig. Technical Report NLL A-1508 A, Nederlands Luchtvaart Laboratorium, Amsterdam, 1963.

[109] J. Markish and K. Willcox. Value-based multidisciplinary techniques for commercial aircraft system design. *AIAA Journal*, Volume 41(10):2004–2012, 2003.

[110] J.N. Martin. *Systems engineering guidebook: a process for developing systems and products*. Systems engineering series. CRC Press LLC, 1997.

[111] W.J. Marx, D.N. Mavris, and D.P. Schrage. A hierarchical aircraft life cycle cost analysis model. In *1st AIAA Aircraft Engineering, Technology, and Operations Congress, Anaheim, CA, September 19-21*, number 1995-3861 in AIAA, 1995.

[112] J.H. McMasters and R.M. Cummings. From farther, faster, higher to leaner meaner greener: further directions in aeronautics. *Journal of aircraft*, Volume 41, Number 1:51–61, 2004.

[113] T.H.G. Megson. *Aircraft structures for engineering students*. Butterworth–Heinemann, third edition edition, 1999.

[114] U.B. Mehta. Guide to credible computer simulations of fluid flows. *Journal of propulsion and power*, Vol. 12, no. 5:940–948, 1996. doi:10.2514/3.24126.

[115] B. Mialon, T. Fol, and C. Bonnaud. Aerodynamic optimization of subsonic flying wing configurations. Number 2002-2931 in AIAA, 2002.

[116] J.H. Miller and S.E. Page. *Complex adaptive systems: an introduction to computational models of social life*. Princeton University Press, 2007.

[117] H.K. Millicer. Sidewash and stability, a study of wing/fuselage interference effects. *Flight*, 1950. 27 July.

[118] Milon. Tornado. note: http://www.redhammer.se/tornado/support.html.

[119] M. Mitchell. *Complexity: a guided tour*. Oxford University Press, 2009.

[120] R.K. Mitchell. Toward a theory of stakeholder identification and salience: defining the principle of who and what really counts. *Academy of management review*, Volume 22(4):853–886, 1997.

[121] A. Morris, P. Arendsen, G. LaRocca, M. Laban, R. Voss, and H. Honlinger. MOB - a european project on multidisciplinary design optimization. In *International Congress of the Aeronautical Sciences*, 2004.

[122] J. Moses. Complexity and flexibility (working paper). 2002. In: Sussman, collected views on complexity in systems.

[123] H. Multhopp. Aerodynamics of the fuselage. Technical Report TM-1036, NACA, 1942.

[124] J.F. Nash. Equilibrium points in n-person games. *Proceedings of the National Academy of Sciences of the United States of America*, Volume 36(1):Pages 48–49, 1950.

[125] J. Naudin. http://jlnlabs.online.fr/gfsuav/index.htm. 2010.

[126] J. von Neumann and O. Morgenstern. *Theory of games and economic behaviour*. Princeton University Press, 1944.

[127] J. Newhouse. *The sporty game*. A.A. Knopft, Inc., 1982.

[128] I. Nikolic. *Co-evolutionary method for modelling Large Scale Socio-technical Systems evolution*. PhD thesis, Delft University of Technology, 2009.

[129] I. Nikolic and G.P.J. Dijkema. Framework for understanding and shaping systems of systems: the case of industry and infrastructure evolution. In *International Conference on System of Systems Engineering*, pages 1–6, 2007.

[130] I. Nikolic and G.P.J. Dijkema. On the development of agent-based models for infrastructure evolution. *Int. J. Critical Infrastructures*, Volume 6, Number 2:148–167, 2010.

[131] A. van Nispen. Slipstream effects on the static lateral and directional control of a multi-engined propeller aircraft with one engine inoperative. Master's thesis, Delft University of Technology, Delft, 2002.

[132] A. van Nispen and R. Slingerland. Propeller slipstream effects on lateral and directional controllability of multi-engined aircraft. In *Society of flight test engineers*, pages 33–26, 2002.

[133] K. Nittinger. 50 years new lufthansa — 50 years of aircraft selection: How to influence the industry. In *44th AIAA Aerospace Sciences Meeting and Exhibit, 9–12 January, Reno, Nevada*, number 2006-0004 in AIAA, 2006.

[134] M.J. North and C.M. Macal. *Managing business complexity: discovering strategic solutions with agent-based modeling and simulation*. Oxford University Press, 2007.

[135] W.L. Oberkampf, T.G. Trucano, and C. Hirsch. Verification, validation and predictive capability in computational engineering and physics. In *Proceedings of foundations 2002, workshop on V&V*, 2002.

[136] W.L. Oberkampf, T.G. Trucano, and C. Hirsch. Verification, validation and predictive capability in computational engineering and physics. *Applied Mechanics Review*, Vol. 57, No. 5:pp. 345–384, 2004.

[137] E. Obert. *Aerodynamic design of transport aircraft*. IOS Press, 2009.

[138] Report of the group of personalities. European aeronautics: a vision for 2020. Technical report, ACARE, 2001. http://www.acare4europe.org/docs/Vision%202020.pdf.

[139] International Civil Aviation Organization. International standards and recommended practices: Environmental protection, annex 16. Technical report, ICAO, 1993.

[140] International Civil Aviation Organization. Assembly resolutions in force. Technical Report Doc 9902, ICAO/CAEP, 2007. note: http://www.icao.int/env/caep.htm.

[141] I. Park, H.K. Amarchinta, and R.V. Grandhi. A bayesian approach for quantification of model uncertainty. *Reliability Engineering and System Safety*, Volume 95:777–785, 2010.

[142] R. Peoples and K. Willcox. Value-based multidisciplinary optimization for commercial aircraft design and business risk assessment. *Journal of aircraft*, Volume 43(4):913–921, 2006.

[143] R.E. Perez, H.H.T. Liu, and K. Behdinan. Evaluation of multidisciplinary optimization approaches for aircraft conceptual design. In *AIAA*, number 2004–4537 in AIAA, 2004.

[144] O. Person, D. Snelders, T.M. Karjalainen, and J.P.L. Schoormans. Complementing intuition: insights on styling as a strategic tool. *Journal of marketing management*, Volume 23(9-10):901–916, 2007.

[145] M.A. Potsdam, M.A. Page, and R.H. Liebeck. Blended wing body analysis and design. Number 1997-2317 in AIAA, 1997.

[146] L. Prandtl. Induced drag of multiplanes. Technical Note 182, National Advisory Committee for Aeronautics, 1924.

[147] L. Prandtl. Induced drag of multiplanes. *Technische Berichte*, Volume III(07), 1924.

[148] E. Qin, G. Yang, and F. Li. Numerical analysis of the interference effect of propeller slipstream on aircraft flowfield. *Journal of aircraft*, Volume 35, Number 1:Pages 84–90, 1998.

[149] D.P. Raymer. *Aircraft design: a conceptual approach*. AIAA Education series, New York, 4th edition, 2006.

[150] E. Rechtin and M. Maier. *The art of system architecting*. CRC Press LLC, 2002.

[151] J.D. Reid. Admissible modeling errors or modeling simplifications? *Finite elements in analysis and design*, Vol. 29:Pages 49–63, 1998. DOI:10.1016/S0168-874.

[152] S.A. Richards. Completed Richardson extrapolation in space and time. *Communications in Numerical Methods in engineering*, 13:573–582, 1997.

[153] S. Robinson. *Simulation: the practice of model development and use*. Wiley, 2004.

[154] E.W.M. Roosenboom, A. Heider, and A. Schroder. Investigation of the propeller slipstream with particle image velocimetry. *Journal of aircraft*, Volume 46, Number. 2:442–449, 2009.

[155] R.S. van Rooyen and M.E. Eshelby. Assessment of propeller influence on lateral-directional stability of multiengine aircraft. *Journal of Aircraft*, Volume 18, Number 4:364–371, 1981.

[156] T.J. Rowley. Moving beyond dyadic ties: a network theory of stakeholder influences. *Academy of Management Review*, Volume 22(4):Pages 887–910, 1997.

[157] G.J.J. Ruijgrok. *Elements of aviation acoustics*. Eburon, 2003.

[158] S. Schlesinger, R.E. Crosbie, R.E. Gagne, G.S. Innis, C.S. Lalwani, J. Loch, R.J. Sylvester, R.D. Wright, N. Kheir, and D. Bartos. Terminology for model credibility. *Simulation*, Vol. 32, No. 3:103–104, 1979.

[159] P.J.H. Schoemaker. Scenario planning: a tool for strategic thinking. *Sloan management review*, Volume 26, Number 2:25–40, 1995.

[160] M.J.T. Schroijen and R. Slingerland. Propeller installation effects on multi-engine propeller aircraft directional stability and control. In *Proceedings of the ICAS 2006 Congress, Hamburg, Germany, Sept. 3-8, 2006*, number 6.10.2 in ICAS. International Council of the Aeronautical Sciences, 2006.

[161] M.J.T. Schroijen and R. Slingerland. Propeller slipstream effects on directional aircraft control with one engine inoperative. In *Proceedings of the 45th AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nevada, Jan. 8-11, 2007*, number 2007-1046 in AIAA, 2007.

[162] M.J.T. Schroijen, R. Slingerland, and L.L.M. Veldhuis. Propeller empennage interaction effects on the vertical tail design of multiengine aircraft. *Journal of aircraft*, Volume 47, Number 4:1133–1140, 2010. doi: 10.2514/1.46707.

[163] M.J.T. Schroijen and M.J.L. van Tooren. Mav propulsion system using the coanda effect. In *45th AIAA/ASME/SAE/ASEE Joint propulsion conference and exhibit, Denver Colorado*, number 2009-4809 in AIAA, 2009.

[164] J. Scott. *Social network analysis: a handbook*. SAGE Publications, 1991.

[165] T-H Shih, W.W. Liou, A. Shabbir, Z. Yang, and J. Zhu. A new K–epsilon eddy viscosity model for high reynolds number turbulent flows. *Computers and Fluids*, Volume 24, Number 3:227–238, 1995.

[166] E.H. Simon. 70 years of transport aircraft development – what did the airlines learn? In *Annual Meeting and Exhibit, Arlington, VA, May 2-4, 1989*, number 1989-1641 in AIAA, 1989.

[167] H.A. Simon. A behavioural model of rational choice. *The quarterly journal of economics*, Volume LXIX:99–118, 1955.

[168] H.A. Simon. A mechanism for social selection and altruism. *Science*, Volume 250:1665–1668, 1990.

[169] P. Smets. What is Dempster-Shafer's model? In R. Yager, M. Fedrizzi, and J. Kacprzyk, editors, *Advances in the Dempster-Shafer theory of evidence*, pages 5–34. Wiley, New York, 1994.

[170] A. Smith. *An Inquiry into the Nature and Causes of the Wealth of Nations*. MetaLibri, 2007. Editor; S.M. Soares, http://metalibri.wikidot.com/title:an-inquiry-into-the-nature-and-causes-of-the-wealth-of-nations:smith-a.

[171] J. Sobieszczanski-Sobieski, J.S. Agte, and R. Jr. Sandusky. Bi-level integrated system synthesis: BLISS. Technical Report TM-1998-208715, NASA, Langley research

center, 1998.

[172] J. Sobieszczanski-Sobieski, J.S. Agte, and R. Jr. Sandusky. Bilevel integrated system synthesis. *AIAA Journal*, Volume 38, Number 1:Pages 164–172, 2000. doi: 10.2514/2.937.

[173] J. Sobieszczanski-Sobieski, T.D. Altus, M. Phillips, and R. Sandusky. Bilevel integrated system synthesis for concurrent and distributed processing. *AIAA Journal*, Volume 41, Number 10:1996–2003, 2003.

[174] J. Sobiszczanski-Sobieski. Sensitivity of complex, internally coupled systems. *AIAA Journal*, Volume 28, Number 1:153–160, 1990.

[175] J. Stuper. Effect of propeller slipstream on wing and tail. Technical Report TM-0874, NACA, 1938.

[176] J.D. Summers and J.J. Shah. Mechanical engineering design complexity metrics: Size, Coupling, and Solvability. *Journal of Mechanical Design*, Volume 132:1–11, 2010.

[177] J.M. Sussman. Collected views on complexity in systems, 2002.

[178] J.P. Sussman. The new transportation faculty: the evolution to engineering systems. *Transportation quarterly*, 1999.

[179] J.P. Sussman. *Introduction to transportation systems*. Boston : Artech House, 2000.

[180] J. Szodruch and R. Hilbig. Building the future, aircraft design for the next century. In *Aerospace Sciences Meeting and Exhibit, 36th, Reno, NV, Jan. 12-15*, number 1998-0135 in AIAA, 1998.

[181] A. von Timme. Uber die geschwindigkeitsverteiling in wirbeln. *Archive of Applied Mechanics, Ingenieur Archiv*, Band XXV, 1957.

[182] E. Torenbeek. *Synthesis of subsonic airplane design*. Delft University Press, Delft, 1st edition, 1982.

[183] E. Torenbeek and H. Deconinck, editors. *Innovative configurations and advanced concepts for future civil aircraft*. Number VKI LS 2005-06 in Lecture series 2005-06. Von Karman Institute, 2006.

[184] S. Tosserams. *Distributed optimization for systems design - an augmented lagrangian coordination method*. PhD thesis, Eindhoven university of technology, 2008.

[185] Engineering Sciences Data Unit. Esdu 79006: Wing body yawing moment and sideforce derivatives due to sideslip: n_v and y_v (with addendum for nacelle effect).

[186] Engineering Sciences Data Unit. Esdu 82010: Contribution of fin to sideforce, yawing moment and rolling moment derivatives due to sideslip, $(y_v)_f$,$(n_v)_f$,$(l_v)_f$, in the presence of body, wing and tailplane.

[187] M.J.L. van Tooren, G. La Rocca, and T.G. Chiciudean. *Further steps towards quantitative conceptual aircraft design*, chapter 27. Springer optimization and its applications. Springer New York, 2009.

[188] V. Vaze and C. Barnhart. Efficient utilization of airport capacity under frequency

competition. In *12th WCTR, July 11–15, Lisbon Portugal*, 2010.

[189] L.L.M. Veldhuis. *Propeller wing aerodynamic interference*. PhD thesis, Delft University of Technology, Delft, 2005.

[190] T.C. Wagner and P.Y. Papalambros. A general framework for decomposition analysis in optimal design. *Advances in design automation*, Vol. 2:Pages 315–325, 1993.

[191] S. Wakayama and I. Kroo. The challenge and promise of blended-wing-body optimization. In *AIAA/USAF/NASA/ISSMO Symposium on Multidisciplinary Analysis and Optimization, 7th, St. Louis, MO, Sept. 2-4, Collection of Technical Papers. Pt. 1 (A98-39701 10-31)*, number 1998-4736 in AIAA, 1998.

[192] D.J. Watts and S.H. Strogatz. Collective dynamics of “small-world” networks. *Nature*, Volume 393:440–442, 1998.

[193] W. Wei and M. Hansen. Impact of aircraft size and seat availability on airlines’ demand and market share in duopoly markets. *Transport Research, Part E*, Volume 41:315–327, 2005.

[194] J. Winchester. *The world’s worst aircraft*. Grange books, 2005.

[195] S. Wolfram. Universality and complexity in cellular automata. *Physical D: Nonlinear phenomena*, Volume 10, 1–2:1–35, 1984.

[196] V.A. Zeithaml. Consumer perceptions of price, quality and value: a means-end model and synthesis of evidence. *Journal of marketing*, Volume 52:2–22, 1988.

Appendix A. Discrete choice analysis

In order to represent the behaviour of stakeholders in a mathematical form, discrete choice analysis is used. Various mathematical representations have been devised to capture the still largely unknown process employed by stakeholder when making a decision for a product.

First the individual decision models are investigated, after which group decision making is investigated. Group decisions are not groups making a single decision, but individuals classified into groups of decisions and this collection of decisions is represented by a single decision model. Finally some considerations on novel technologies are

A.1 Individual decisions

Discrete choice models investigate and quantify the choices made by an individual or organization from a finite set of discrete alternatives. Each alternative has a value or utility function which is determined by the product properties (attributes) as well as the satisfaction (value) derived from each of these attributes compromising the alternative. The value of each alternative is considered to consist of,

$$U = \boldsymbol{\beta}\mathbf{x} + \xi \tag{A.1}$$

where $\boldsymbol{\beta}$ is the (normalized) valuation vector of (considered) product attributes by the person making the choice, $\boldsymbol{x}$ the attribute vector, consisting of the attributes considered by the investigator, and ξ a scalar to account for the unconsidered attributes. Assuming multiple alternatives, requires multinomial models, where multinomial means considering more than two alternatives (i.e. three or more), in contrast to binomial models. Within this class, two large subclasses exist, considering either no-correlation or correlation between choices.

A.1.1 No-correlation between alternatives

The conditions which need to be satisfied by each choice are that the choice set must be 1) exhaustive, 2) mutually exclusive and 3) finite. Within this class two alternatives exist; 1) all alternatives are rated on the same attribute vector $\mathbf{x}$, or 2) each alternative is rated on its own (possibly different) attribute vector $\mathbf{z}$.

Considering ratings on equal attribute vectors, the distribution of ξ is assumed to be logistic,

$$f(\xi, \mu, s) = \frac{e^{(\xi-\mu)/s}}{s\left(1 - e^{(\xi-\mu)/s^2}\right)} \tag{A.2}$$

hence creating a multinomial logit model. The probability that the individual chooses alternative p from the set of C choices then becomes

$$\mathcal{P}(p) = \frac{e^{\boldsymbol{\beta}\mathbf{x}_p}}{\sum_{p\in C} e^{\boldsymbol{\beta}\mathbf{x}_p}}. \tag{A.3}$$

The probability that the individual chooses alternative i when a ranking on different product attributes is considered,

$$\mathcal{P}(p) = \frac{e^{\boldsymbol{\beta}\mathbf{z}}}{\sum_{p\in C} e^{\boldsymbol{\beta}\mathbf{z}}}. \tag{A.4}$$

A.1.2 Correlation between alternatives

In the correlation case, the previous assumptions are somewhat relaxed. Many correlations can be specified between choices, here only the nested multinomial logit model is considered[17].

Distribute all choices C (mutually exclusive, exhaustive and finite) into nests C_n,

$$C = \cup_n C_n, C_n \cap C_{-n} = \emptyset \tag{A.5}$$

The utility function is considered to consist of two parts, 1) specific to the product within the nest, 2) specific to the nest considered,

$$U = U_{C_n} + \xi_{C_n} + U_p + \xi_p \tag{A.6}$$

the terms ξ_{C_n} and ξ_p are assumed to be follow a logistic distribution. The composite utility for the nest can then be derived as follows,

$$U'_{C_n} = U_{C_n} + \frac{1}{\sigma_n} \ln \sum_{p\in n} e^{\sigma_n U_p} \tag{A.7}$$

the resulting probability can be interpreted as a combination of the probability of choosing a particular nest and the probability of choosing alternative p within that nest,

$$\mathcal{P}_C(p) = \mathcal{P}_C(C_n)\mathcal{P}_{C_n}(p) \tag{A.8}$$

with the probability on nest choice

$$\mathcal{P}_C(C_n) = \frac{e^{\mu U'_n}}{\sum_n e^{\mu U'_n}} \tag{A.9}$$

and alternative choice within nest,

$$\mathcal{P}_{C_n}(p) = \frac{e^{\sigma U_p}}{\sum_{p\in n} e^{\sigma U_p}} \tag{A.10}$$

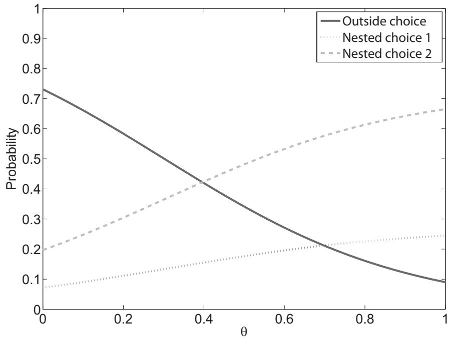


Figure A.1: Nested multinomial logit model and effect of θ, $V_0 = 1, V_1 = 2, V_3 = 3$

only the relation between σ and μ is important, and is limited to

$$0 \leq \frac{\mu}{\sigma} \leq 1 \tag{A.11}$$

if $\frac{\mu}{\sigma} = 1$ the correlation between alternatives within the nest equals zero and the multinomial logit model is once again obtained.

An alternative formulation using outside choice, where an outside choice is defined as not choosing an alternative considered, have been used by Wei and Hansen[193],

$$\mathcal{P}_C(p) = \frac{\left(\sum_{p \in C_i} e^{V_p}\right)^{\theta}}{e^{V_0} + \left(\sum_{p \in C_i} e^{V_p}\right)^{\theta}} \frac{e^{V_p}}{\sum_{p \in C} e^{V_p}} \tag{A.12}$$

and the parameter $theta$ is limited between 0, where the value of the alternatives within the nest has no influence on the choice for the nest, and 1 where the un-nested multinomial logit model is obtained. The effect of the nested parameter θ is shown in Figure A.1

A.2 Group decisions

For group decisions the choice probability representation derived in the previous section is interpreted as an in–group choice frequency. As a consequence, even though not all group members make the same choice, they are assumed to have the same preference distribution. In order to be able to interpret the group decision like this it has to be assumed that each individual's decision is taken independently and simultaneously. That is the utility representation is independent from the other group members choices. This is generally not the case due to positive externalities arising, e.g. cheaper support and better service, in case more individuals choose similar products.

If these assumptions are satisfied, the number of individuals, Q_p, choosing alternative, p from a total number of individuals Q_m, is given by,

$$Q_p = Q_m \mathcal{P}_C(p) \tag{A.13}$$

where $\mathcal{P}_C(p)$ is determined by the choice procedure employed by all individuals in the group.

A.3 Determining attribute valuation

The previously derived individual and group decision rules, represented by Equations A.4, A.4, A.8, A.12 and A.13 respectively, are used to determine the attribute valuations in the utility function. The use of product market shares to identify the attribute valuation is a commonly used revealed preference method[17, 18, 193]. The focus is on the differences between the available products and the resulting effect on the market share. The non-uniqueness of the utility function is represented by the relative nature of the results, i.e. one product utility is taken as a reference, U_0 to which all other utilities are scaled. A selection of the attributes under consideration — often dependent on the availability of the data — and their representation in the utility function has to be made. Consequently, assume a certain utility function $U(\boldsymbol{x})$, dependent on the attributes of interest.

A.3.1 Coupling utility and market share

Equation A.13 gives a possible relation between the utility of the product and the number of individuals choosing the product. The relation between market share of the reference product 0 and its value V_0 is consequently given by:

$$Q_0/Q_m = \frac{e^{U_0-U_0}}{e^{U_0-U_0}+\sum_p e^{U_p-U_0}} \tag{A.14}$$

where $p \neq 0$. This equation provides a non–unique dependency between the observed market share, the reference product value and other products. For the other products p a similar relation is given by,

$$Q_p/Q_m = \frac{e^{U_i-U_0}}{e^{U_0-U_0}+\sum_p e^{U_p-U_0}} = \frac{e^{U_p-U_0}}{Q_0/Q_m} \tag{A.15}$$

taking the logarithm and simplifying results in,

$$\ln Q_p - \ln Q_0 = U_p - U_0 \tag{A.16}$$

setting U_0 thus determines all U_p relative to this chosen value.

A.3.2 Obtaining attribute valuations

Depending on the data set available, i.e. the product attribute values and the respective market shares of the available products, the attribute valuations can be determined. Assuming one measurement point over a period, each period data set provides information on one additional attribute, if the products attribute values on that attribute are sufficiently different. Assume a utility function of the form,

$$U_p = \alpha F_p + \boldsymbol{\beta}\boldsymbol{x} + \xi_p \tag{A.17}$$

Furthermore, assume that the changes in group preferences are small. Furthermore the distribution of ξ_p is assumed to be logistic by assuming the previously considered market share distributions. For a given customer group, Equation A.16 can be rewritten as

$$\ln Q_p - \ln Q_0 = \alpha(F_p - F_0) + \boldsymbol{\beta}(\boldsymbol{x}_p - \boldsymbol{x}_0) + U_p - U_0. \tag{A.18}$$

Where it is assumed that the reference value $U_0 = 0$. Given a data set of market shares Q_p, product data $\boldsymbol{x}_p$ and prices F_p, the values for the options can be derived using a least squares method[1]

$$[\boldsymbol{A}] \begin{bmatrix} \alpha \\ \boldsymbol{\beta} \\ \boldsymbol{U}_p \end{bmatrix} = \boldsymbol{b} \tag{A.19}$$

where $[\boldsymbol{A}]$ is a matrix describing the differences in attribute values and $\boldsymbol{b}$ the difference in logarithm of market share plus the value assigned to the reference product U_0.

$$b = \ln Q_p - \ln Q_0 + U_0 \tag{A.20}$$

The important conclusion is that attribute values not measurable cannot be included in the utility function using this method. Furthermore, the method is based on difference in attribute values. As a consequence, product sets consisting of similar alternatives — equal attribute values — do not provide answers to the valuation of that attribute. For a novel technology, where product attribute values might differ from the previously similar product alternatives, this utility derivation method provides an incorrect prediction of the market share. Consequently the results of models based on these inferences for novel technologies should be treated with the utmost care.

---

[1] Other methods statistical fitting methods are available, however are subject to the same limitations.

Appendix B. Airline behaviour in the air travel market

Chapter 3 describes two markets and their interactions. utility functions are proposed for each of the stakeholders. The characteristics of the airline and passenger interactions originating by these functions is addressed in this appendix to support and clarify the claims.

B.1 Airline behaviour model

To illustrate the effect of the interactions, the relation between the passengers and the airlines is investigated. Additionally, the impact of a novel technology on this behaviour is investigated, as well as the effect of operational restrictions. Furthermore, the considerations are extended to address the multiple routes serviced by airlines. Finally the simplification employed on passenger choice and its effect on the strategy is considered. Throughout this appendix the following data are assumed: Cost per flight C: 10,000, Fare F: 100, Number of seats available per aircraft S: 200 and the Saturation demand Q_m: 4000. These values are chosen to illustrate the specifics of airline behaviour and have not been based on any existing airline-route combination. For a validation of the decision model the reader is referred to Vaze and Barnhart[188].

B.1.1 Airline strategy

Consider a single route market, consisting of competing airlines i and $-i$. Both set their flight frequencies simultaneously (e.g. at the beginning of the year). The saturation demand for the route under consideration is Q_m and is split among the airlines according to a multinomial logit model[17, 193]. Wei and Hansen[193] quantified the preferences for demand and obtained the valuation of specific parameters — frequency, aircraft size (measured in seats per flight), seat availability, and fare — for certain domestic US routes. One of the determining parameters was the frequency of service provided. Frequency can also be reformulated as schedule delay[102], which is classified as the difference in time the passenger ideally would want to fly and the actual time of flight. The potential difference between the two decreases with increasing frequency, resulting in a smaller value degradation. Due to its direct correlation to the operation of the aircraft, and the high correlation

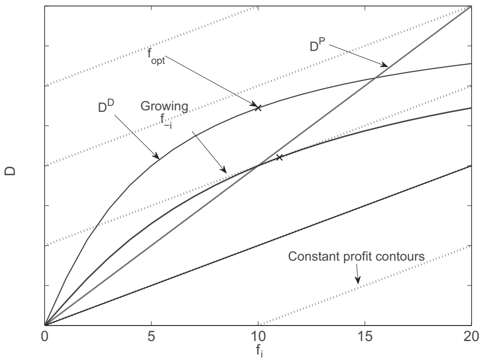


Figure B.1: Schematic airline profit function, for a single route and single competitor.

to value, this parameter will be used for the investigation.

$$D^D_{i/-i} = Q_m \frac{f^\alpha_{i/-i}}{f^\alpha_{-i} + f^\alpha_i}, \tag{B.1}$$

neglecting the choice for alternative modes of transportation. The coefficient α represents the passenger preference for frequency, a value of 1.094[193] is used. Both services are considered to be distinguishable from each other by unconsidered items. Q_m in this example consists of all passengers already having decided to fly, in contrast to Equation 4.7, θ is consequently assumed to be 0 as demand for this nest is not affected by utility in air travel, contrary to the value of 0.584 found by Wei and Hansen[193].

The resulting profit function for airline i is given in Figure B.1. The profit is determined by the frequency f_i of the airline as well as its competitors frequency f_{-i}. The figure shows that for small frequencies the satisfied demand Q is either limited by the capacity provided,

$$D_i \leq S_r f_i = D^P \tag{B.2}$$

or the passenger demand requested, Equation B.1.

$$D_i \leq D_D \tag{B.3}$$

Furthermore, the frequency might be limited by the total frequencies or slots available,

$$f_i \leq f_m, f \in \mathbb{N}, \tag{B.4}$$

for the moment this constraint is not considered. The problem is consequently formulated as a constrained integer optimization problem which is tackled using an iterative dynamic programming approach[15]. This procedure assumes that the solution of airlines iteratively selecting frequencies converges to the same solution when both frequencies are chosen simultaneously[188]. This iterative procedure is required to incorporate the influence of the frequency selection of the airlines onto each other. The information exchange, and resulting mutual influence of the airline, consequently takes place via the passengers, as shown in Figure B.2.

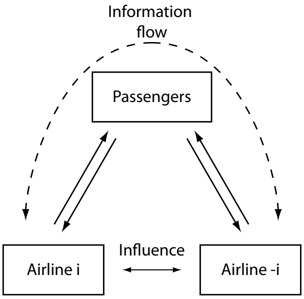
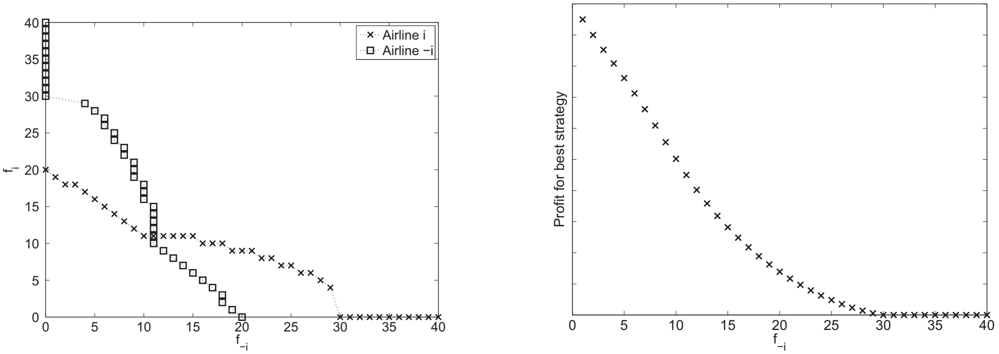


Figure B.2: Information exchange via the passenger market.



(a) Airline best response strategy.

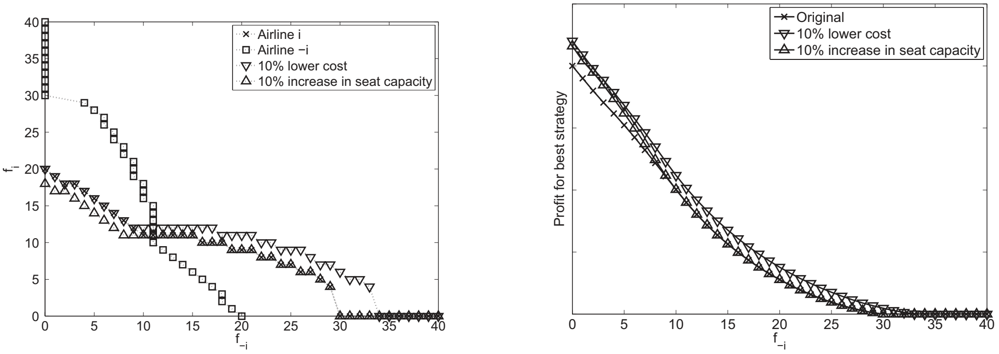
(b) Airline best strategy profit.

Figure B.3: Airlines best response strategy for a given competitor strategy.

B.1.2 Best strategy

The resulting best strategy is shown in Figure B.3a. Note that the staircase profile exists due to the limitation of integer values for frequencies. The airline strategy without the capacity constraint is probably most easily understood; substitute $D_i = D_i^D$ and choose the frequency which maximizes profit. Including the capacity constraint forces the airline to increase the frequency to be able to accommodate the demand D^D up to the point where demand is no longer increasing to match the increase in capacity. Once sufficient capacity is provided, this capacity constraint becomes inactive and the original strategy applies. The corresponding profit is depicted in Figure B.1, denoted by ○, and is seen to decrease from the competitor choosing $f_{-i} = 0$ to $f_{-i} = 40$. The maximum attainable profit for an increasing competitors frequency decreases. Any profit for the competing airline $-i$ therefore comes at the expense of airline i, consequently this game is a characterized as a zero-sum game[105].

The symmetry in this problem dictates that the competing airline faces the same issue. Assume 2 identical airlines (i.e. identical cost and revenue structures). Both best strategy curves are plotted together in Figure B.3a. This figure displays both airlines' chosen frequencies on the axis and their corresponding best responses to these frequencies. Con-



(a) Airlines best response strategy.

(b) Airline best strategy profit.

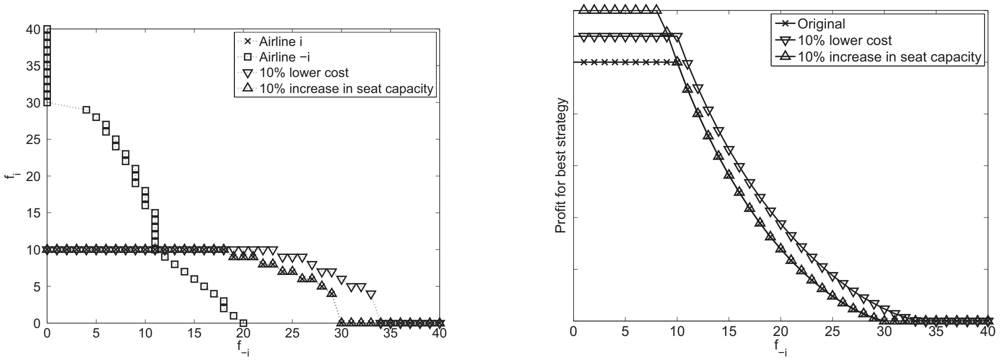
Figure B.4: Airlines best response strategy for a given competitor strategy, including novel technology.

sider that airline i sets its frequency to 20, the best strategy for airline $-i$ would be to set its frequency to 9. In this situation, $f_{-i} = 9$, airline i can do better than its original choice by choosing a frequency of $f_i = 11$. Alternatively, the chosen frequency $f_{-i} = 10$ is not optimal in this case, which results in a selection of airline $-i$ of 11 as well. No better strategy is possible for either airline. This equilibrium, where neither airline can do better by unilaterally changing their strategy, is called the Nash equilibrium[124]. Here the Nash equilibrium is stable since the best strategies converge towards it. In conclusion, the best strategy of either airline, when considering the other airlines strategy, would be to select the frequency corresponding to the Nash equilibrium.

B.1.3 Introduction of novel technology

Up to this point the airlines were considered to have an equal cost structure and consequently equal profit function, and only appropriate selecting of the frequency could be employed to maximize profit. Introducing a novel technology, might have both an effect on the revenue side as well as the cost side. No account has be taken for the implementation considerations, like purchase costs, availability and suitability in the airline. Assume a two novel aircraft having properties, $S_n > S$ and $c_n < c$ respectively. The effect of the cost reduction, seen in Figure B.4b, results in an overall increase in profit as well as a slight change in optimal frequency, depicted in Figure B.4a. The effect of the increase in capacity is much less drastic and even absent in the region where ample capacity was already available ($f_i \geq 10$). In the capacity constrained region however the profit is seen to increase as more passengers can be transported for equal flight frequencies. Only the cost reduction shifted the Nash equilibrium from $\{11, 11\}$ to $\{12, 11\}$, increasing the number of flights. The capacity changes considered (10% increase) are too small to make definite conclusions about the change in equilibrium. However, a shift point where both constraints are active can be seen, from $f_{-i} = 9$ to $f_{-i} = 7$.

Often airports pose constraints on the number of slots available to the airlines. To evaluate the effect of this additional constraint an additional constraint is imposed solely on airline



(a) Airlines best response strategy.

(b) Airline best strategy profit.

Figure B.5: Airlines best response strategy for a given competitor strategy, including novel technology and airport constraints.

i,

$$f_i \leq 10. \tag{B.5}$$

This additional constraint results in different responses and profit functions for the two technologies, as seen in Figure B.5. Here the effect of the capacity increase is more significant, whereas the cost reduction still has an overall improvement of the profit function. Furthermore, the Nash equilibrium point has shifted to $\{10, 11\}$. Overall profit has increased, however the options provided to passengers are limited. Consequently the LOS has decreased due to the introduction of this constraint, for this specific example.[1]

B.1.4 Multiple routes

For the one route considered the optimization strategy appears to be a waste of computational resources, however for multiple routes and competing airlines this approach is more justified. Using the Bellman equation[15],

$$P(r, f_{i,r}) = \pi(f_{i,r}) + P(f_m - f_{i,r}, r - 1) \tag{B.6}$$

which optimizes the profit by selection appropriate frequencies, $f_{i,r}$ over all routes r. This optimum does not include the influence of airline $-i$ on the passenger demand yet. Due to the Nash stability an iterative procedure is employed to find this equilibrium for the selected frequencies.

B.1.5 Limitations to the current implementation

The feedback among airlines, implemented by the effect of frequency on demand, affects the strategy chosen by the airline, i.e. behaviour. This implementation assumes that the

---

[1] The LOS in the broader sense might have increased, as less passengers might result in shorter lines near customs, security and at the check-in desks.

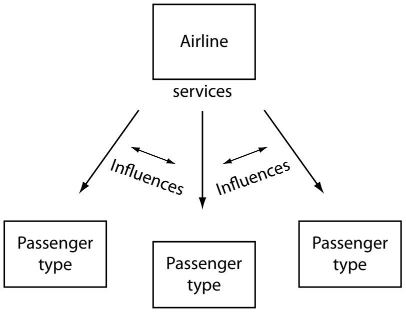


Figure B.6: Links among passenger types due to the availability of services.

airlines are both aware of the concept and follow it rationally. This might be compromised due to incomplete or incorrect information on each of the routes passenger preferences, demand and competitor products. In addition to this limitation on airline knowledge, the information exchange incorrect interpretation of the product data also occurs on the passenger side[103]. Passengers might expect a certain service, which is not met by the actual product[30, 196]. Furthermore the simultaneous selection of frequencies is required, otherwise the airline first selecting the frequency could force the second one into a different equilibrium — e.g. Stackelberg equilibrium. This rationale is not included in this model.

The behaviour of the passengers might equally change if they are considered to transfer information among each other. Currently passengers are considered to make their choice simultaneously and independent of each other. Examples of information transfer and feedback among passengers would be the desire for group travel of passengers, unwillingness to travel in an over–crowded aircraft and last minute decisions guided by the availability of seats. The last example is elaborated in more detail to illustrate the consequences for the airline strategy. Often similar seats in an aircraft are part of a different air-travel service product. Consequently, the seats can be sold on different products for different types of passengers. The result is that the services provided by the airline are coupled and the decision of a passenger to select a seat affects the choice of the other potential passengers. This is shown in Figure B.6. The multinomial model employed in the previous sections has no criteria for estimating which passengers are not able to obtain a seat. According to the previous considerations on passenger types, are likely to be the high revenue passengers if no special measures are taken to control the seat availability[16]. Airlines have strategies to cope with these difficulties[16], however they are not reflected in the current model. Consequently, the model results are likely to be different from real behaviour.

B.2 Behavioural effect on externalities

The impact of novel technology on the airline behaviour has been investigated in the previous section. Considering that every action has an external effect, it is clear that this changed behaviour also affects the externalities of aviation. The environmental impact of these behaviour changes have not yet been considered. Assume an external impact which is directly caused by the choice of frequency and dependent on the technology used,

$$\psi = \psi(f). \tag{B.7}$$

For multiple airlines, the total external impact of their actions is a function of all frequencies,

$$\psi = \psi(f_i, f_{-i}), \tag{B.8}$$

where f_i, f_{-i} are coupled by the information exchange in the passenger market as shown in Figure B.2. Assume that a linear relationship exists between the frequency and the external impact. This is the case for carbon-dioxide emissions which are directly related to fuel flow. Assuming that on a single route the fuel per trip is constant, despite variations in payload, the cost and emissions can be written as a function of the frequency,

$$\psi = \frac{\Delta\psi}{\Delta f}\sum_i f_i \tag{B.9}$$

where $\Delta\psi/\Delta f$ is the impact per frequency (IPF). Introducing a novel technology is seen to influence the frequency choice, but might also affect the impact per frequency. Considering a technology which decreases costs and impact per frequency — carbon-dioxide is related to fuel burn, which comprised 30% of 2008 direct operating cost.
Consider the two airlines previously considered $i, -i$. Their combined impact in the original Nash equilibrium is equal to $\psi = 22$IPF.

$$C_f = C(\psi) + C, \tag{B.10}$$

where $C(\psi)$ is the part of the costs affected by the environmental impact and C_0 the part not affected. Assuming a linear relation between environmental impact and costs,

$$C_f = \frac{\partial C}{\partial \psi}\psi + C \tag{B.11}$$

if the example of carbon dioxide emissions is used, C equals $2/3$ of $C_0 = 10,000$, and assuming constant fuel prices, a percentage decrease in emissions results in an equal decrease in costs percentage,

$$C_f = \xi\frac{C_0}{\psi_0}\psi + (1-\xi)C_0, \tag{B.12}$$

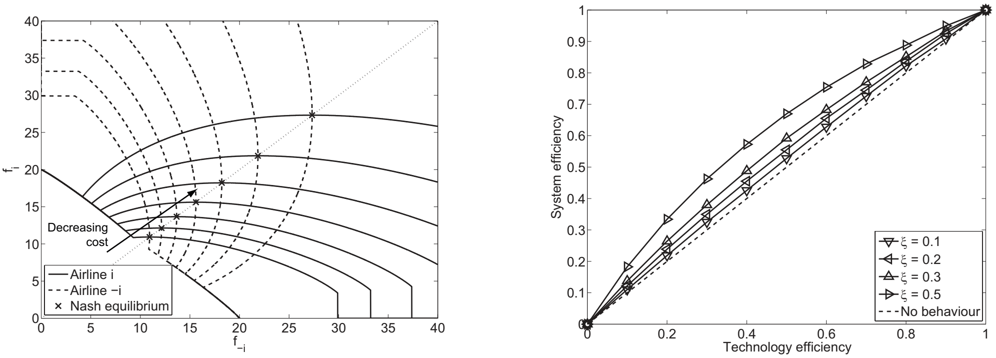
where ξ equals the fraction of the costs affected by the environmental impact. In this case $\xi = 1/3$ Assume airline i introduces a novel technology with the following properties; impact per frequency is reduced by 30%, the resulting cost reduction is 10%, airline $-i$ does not incorporate this technology. The effect is equal to the previously considered scenario of the more cost effective technology. The resulting impacts of the technology accounting for the change in behaviour are shown in Table B.1. The results for not incorporating the system, label 0 and for one airline incorporating the system, label 1, are given for each of the airlines and the system–of–systems. The impact reduction — 12% — is lower than the expected reduction — 15% —, caused by the changed behaviour of the airline[2]. Often, the technology is not limited to one airline. In response, the competing airline might also opt to incorporate this technology. These results are given in the third column labelled 2

---

[2] Efficiency improvement is determined by $1 - \frac{\psi_N}{\psi_0}$.

Table B.1: Environmental impact in various scenarios.

N systems used	0	1	2
Airline i	11	$0.7 \cdot 12$	$0.7 \cdot 12$
Airline $-i$	11	11	$0.7 \cdot 12$
Total	22	19.4	16.8



(a) Optimal strategies for various cost reducing technologies.

(b) Environmental impact for various cost fractions ξ.

Figure B.7: Combined behaviour and technology effect on the environmental impact.

in Table B.1. The system improvement in environmental impact of 24% is lower than the expected 30%. Due to the inelasticity of the total saturation demand, the total number of passengers transported has not changed.

In conclusion, for a saturated market, the best strategy for the airline investing in the lower cost technology is to increasing frequency and capture a larger market share. This additional market share and resulting profit increase are necessary to justify the technology investment. On the other hand, although the overall impact was reduced, it was not reduced to the extent expected from the efficiency gain at the technological level,

$$\Delta\psi_{\text{technology}} \neq \Delta\psi_{\text{system}}. \tag{B.13}$$

This behavioural affect needs further investigation but it is clear that it is important in the achievement of global environmental targets. The effect of efficiency improvement on optimal frequency is schematically depicted in Figure B.7a. Mutual adoption of technology, which is linearly increasing in efficiency, increases the optimal frequency more than linearly — each subsequent line represents a 10% reduction in costs from the original costs, C. The resulting environmental impact is given in Figure B.7b, for various cost fractions ξ, as defined in Equation B.12. For increasing fractions of cost, i.e. increasing system efficiency, the discrepancy between system and system-of-systems becomes more pronounced. As a consequence, the larger the effect of the environmental impact on the value inducing changed behaviour, the more important the considerations on behaviour become. For definite conclusions, a realistic case should be investigated.

Appendix C. Information effect on behaviour

The behaviour of the manufacturer behaviour is assumed to be guided by profit maximization as determined in Chapter 3. One of the issues in launching a new product is appropriate product placement, i.e. selecting the correct attribute values for this product. This issue has been identified in Chapter 4 and Appendix A. The effect of a possible incorrect perception alters the behaviour of the aircraft manufacturer. This effect is investigated on the basis of a hypothetical duopoly with single aircraft producing manufacturers.

First the behavioural model as implemented in the simulation is presented and discussed. Subsequently, three cases and the results are investigated using various manufacturer behaviour implementations, focussed on the determination of the airline utility function. The main focus of this appendix is to support the claims made in Chapter 4, using an illustrative example.

C.1 Behaviour

The aircraft market price setting is characterized by two effects: 1) the strong effect of the learning curve on the price setting of aircraft, 2) the possible incorrect prediction of attribute valuations. The first effect has been investigated by among others Benkard[18] and focussed on the predicted number of aircraft sold in the program and setting the price accordingly. Mainly for two reasons, 1) to progress down the learning curve as quickly as possible to reduce marginal costs and 2) to meet the production required to prevent organizational forgetting. Consequently this important effect on the pricing behaviour is implemented in the profit function of the manufacturer.

In order to capture the behaviour of the manufacturer, its profit function, based on the airline utility function is determined. After which the environment in which the agents are allowed to interact is presented.

C.1.1 Utility functions

The aircraft manufacturer has to estimate the number of aircraft to be produced in a time period to provide sufficient production capacity for that period. The number of aircraft sold can be influenced by the affecting aircraft value. In general the quality of aircraft is seen to improve during its lifetime, for instance by increases in payload capability or range. For this evaluation this is assumed not to be the case. The actual demand on the other hand is determined by the selection of products by the airlines, represented by a multinomial logit model. This is not in correlation to the real world multi-aircraft buying strategy of airlines and lease companies, but is considered a reasonable first approximation[18]. The number of aircraft expected to be sold is determined by the airline utility function, which is assumed to be of the form,

$$V_i = V_0 - \alpha F_i + \xi. \tag{C.1}$$

Assuming that the cumulative decisions can be represented by a nested logit distribution, the demand for aircraft i is given by,

$$Q_i = Q_T \frac{\left(\sum_i e^{V_i}\right)^{\theta}}{e^{V_E} + \left(\sum_i e^{V_i}\right)^{\theta}} \frac{e^{V}_{i}}{\sum_i e^{V_i}}. \tag{C.2}$$

Increasing market share can thus be achieved by increasing value V_i[1], i.e. better product or decreasing price p. For the hypothetical aircraft the attributes discussed earlier in Chapter 3, can be used to determine the value function in relation to the other aircraft. However, product quality is difficult and expensive to adapt once the aircraft has been designed and certified. As a consequence, the price is considered the most important factor. Henceforth assuming that the quality of the aircraft is fixed, direct competition is therefore considered to be based mainly on price for a fixed aircraft quality. The airlines aircraft choice is represented by an un-nested multinomial logit function

$$Q_i = Q_T \frac{V_i}{\sum_{-i} V_{-i} + V_i}, \tag{C.3}$$

where the aircraft value function is determined by

$$V_i = V_0 - \alpha F_i \tag{C.4}$$

On the cost side a strong learning curve effect is present in aircraft manufacturing. This learning curve originates from the fact that due to learning each subsequent aircraft can be produced at lower costs. This learning curve has a direct effect on the price setting of the aircraft[18]. Assume that the learning curve effect can be represented in the marginal costs of the qth aircraft by

$$c_q = c_0 q^{-e} \tag{C.5}$$

the marginal costs of producing Q aircraft consequently are

$$C = \sum_{q=1}^{Q} c_0 q^{-e}. \tag{C.6}$$

---

[1] For the case $\theta = 0$ only relative value to competitor is addressed.

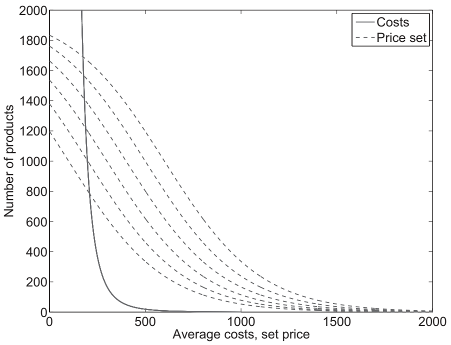


Figure C.1: Demand curve ($Q - F$) and demand average cost per unit curve ($Q - C$). ($\alpha = 0.004, V_0 = 1, e = 0.3, c_0 = 1000$)

Finally, a batch of aircraft from Q_0 to Q_1 costs

$$C(Q_0, Q_1) = \sum_{q=Q_0}^{Q_1} c_0 q^{-e}. \tag{C.7}$$

representing the decrease in average costs per aircraft with increasing numbers of aircraft produced.

Combining both considerations allows for the creation of a profit function

$$\pi = Q_i^a F_i - C(Q_0, Q_1) \tag{C.8}$$

where Q_i^a is the minimum of the predicted amount of aircraft — limited by production capacity — and the actual demand. The costs are determined by the number of aircraft predicted.

The two effects, influence of price on demand and number of aircraft of average production cost is shown in Figure C.1. The multiple “price set” lines represent the effect of the competitors price on the demand. An increasing competitor price results in an increased demand. Therefore, the lines from lower left to upper right represent an increase in competitors price.

C.1.2 Agent implementation

The effect of the competitor price on the demand requires additional, dynamic information on the competition of the — heterogeneous — manufacturers. For this purpose an environment is created in which the aircraft manufacturers are allowed to make decisions. Schematically the representation and interaction of the two agent classes, aircraft manufacturer and airline, as well as the environment class is shown in Figure C.2. The behaviour of both agents is split into observation, interpretation and manipulation of or interaction with the environment.

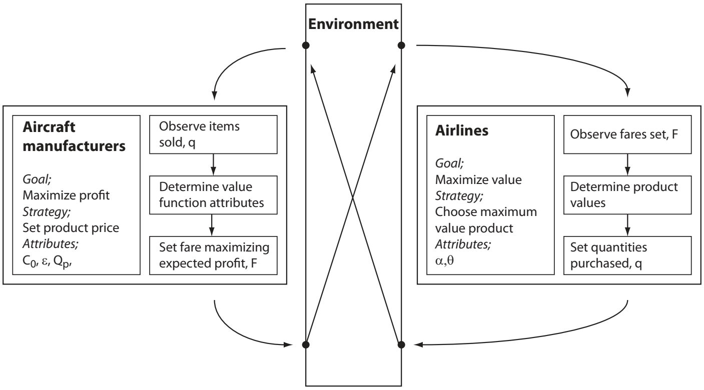


Figure C.2: Schematic data flow through the elements of the simulation.

Table C.1: Simulation manufacturer properties.

	V_0	α	θ	ϵ	c_0
M_1	1.0	0.004	1.0	$\ln 0.85/\ln 2$	1000
M_2	1.0	0.004	1.0	$\ln 0.85/\ln 2$	1000

C.2 Results

Three cases are investigated 1) homogeneous manufacturers with perfect information, 2) homogeneous manufacturers with imperfect information and 3) heterogeneous manufacturers with imperfect information. In the first case the aircraft manufacturers have all information available in the model at their disposal to estimate and react to the changing environment. In the second case, the preferences of the airlines are not known to the manufacturer agents and require an estimation. Finally the manufacturers are assumed to have different cost structures and imperfect information. The effect off each of these cases on the behaviour is determined.

C.2.1 Homogeneous manufacturers with perfect information

Assume two aircraft manufacturers providing distinguishable aircraft with equal values V_0. The strategy employed by either manufacturer is to set the price to maximize predicted profit. This set price incorporates the price set by the competing manufacturer in the previous time period. A best response diagram is given in Figure C.3 for the values employed for the hypothetical aircraft are given in Table C.1 and a market size of $Q_T = 25$. The resulting behaviour is given in Figure C.4a. Both manufacturers converge to a similar price. Furthermore the difference in predicted and actual profit is seen to converge to zero. This can be seen as learning behaviour. This simulation is limited to the influence of both manufacturers on each other. Demand is not constant as assumed, the results for assuming a (uniformly chosen) random demand between $Q_T \in [5, 45]$ still converge to similar price

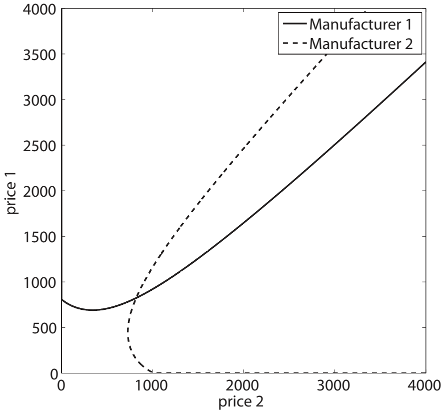
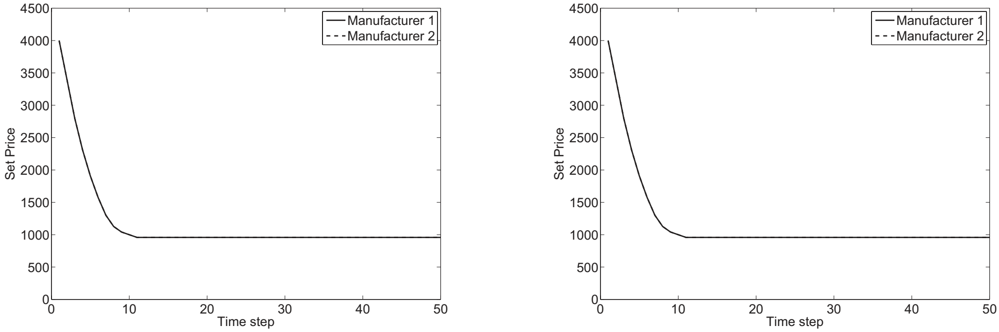


Figure C.3: Best response for a given competitors fare.



(a) Perfect information. (b) Random changes in product valuation

Figure C.4: Resulting price setting for perfect information.

values. Consequently the overall demand is considered of less importance than the manufacturer behaviour, with respect to the stability of the system. Even when preferences, or sensitivity towards price, are randomly changing within bounds, the behaviour results in a convergence towards an attractor as illustrated in Figure C.4b. The Nash equilibrium is consequently considered to be stable in terms of equilibrium position for two similar aircraft manufacturers and homogeneous products.

C.2.2 Homogeneous manufacturers with imperfect information

Reality however does not provide a perfect information situation. Preference information has to be derived from (previous) years sales data and/or interviews with customers. To mimic this imperfect information in the simulation, each manufacturer keeps track of previous years sales data and uses a least squares methodology to estimate V_0 for all products as well as α. The employed values are equal to the ones used in the previous case, i.e. given by Table C.1. These values are determined by a least squares method from market

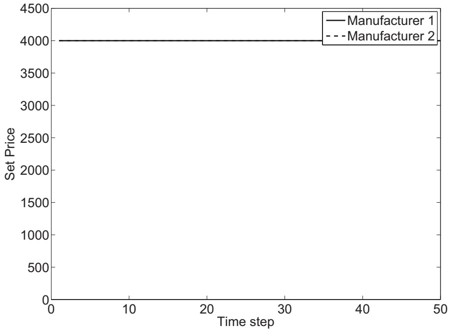
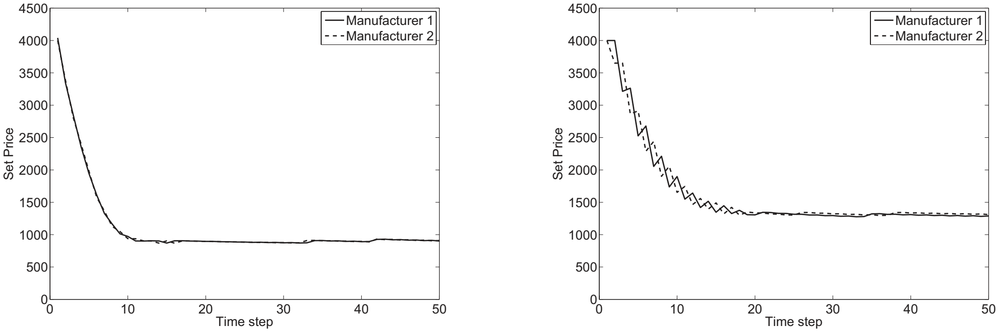


Figure C.5: Resulting behaviour with imperfect information and symmetric manufacturers.



(a) Asymmetric product cost.

(b) Heterogenous behaviour model.

Figure C.6: Resulting behaviour with imperfect information and asymmetric manufacturers.

demand by each of the manufacturers and its actions are based on this approximation. Equation A.19 from Appendix A is used for this. For homogeneous manufacturers and products and deterministic market demand, this results in completely different behaviour with respect to the previous case. In the symmetric situation, both manufacturers employ the same pricing strategy. This results in a zero difference in product pricing, hence the price sensitivity α remains undetermined. Randomness on the valuation of the product is also ineffective; both manufacturers use the same database consequently, the difference in fares remains zero. As a consequence the price selected is the maximum allowed price of 4000, this is artificially bound in the problem to reduce computation time. Without limit the price would have been set at ∞, in order to maximize profit.

C.2.3 Heterogeneous manufacturers

The symmetric situation with imperfect information results in symmetric behaviour and the inability of both manufacturers to identify the sensitivity with respect to price. In terms of price this symmetry does not exist, however, indistinguishable attributes do exist in reality.

To distinguish between these attributes the symmetry needs to be broken. Asymmetry in this simulation can be created by difference in 1) products or 2) behaviour. The difference in products is set by increasing the first product cost c_0 from 1000 to 1100. The resulting behaviour is shown in Figure C.6a. The fares converge to the same equilibrium as the a symmetric perfect information situation. Consequently asymmetric product attributes are required to determine the customer attitude, i.e. sensitivity, with respect to the product attribute. An alternative means of creating asymmetry is by incorporating different behaviour. For this case it is assumed that one manufacturer has perfect information whereas the other has to estimate the preferences. This can be seen as an incumbent and an newcomer to the market. The resulting behaviour is shown in Figure C.6b. The results again converge to the same price equilibrium.

Appendix D. Technology adoption

In order for the sustainable technologies to be implemented, a forced introduction is considered inefficient and even impossible. Technology introduction by legislation is limited to regions where the rules apply. Furthermore, legislation might result in unfair competition between companies forced to incorporate the technology and others, when both are competing in the same market. A more efficient method of implementing sustainable technologies is considered if technologies spread “naturally”, i.e. the stakeholders adopt the technologies voluntarily. The time to complete adoption of the technology, and how this is influenced by the environment of the decision makers requires further investigation. This requires information on the effect of the environment on the choice for a technology. This is a step away from the simultaneous, independent choices and includes the changing environment of the stakeholder.

The decision of the airline for a new aircraft is considered as an example. For the airline value is considered to be the most important for the stakeholder to incorporate the technology. The aircraft manufacturer can influence the value of the product by

- an adaptation of the system, e.g. increase satisfaction or increase functionality
- adapt cost, e.g. decrease price or operational costs

This consideration is limited to the manufacturer–airline relation. However other influences beyond the control of the manufacturer exist which affect the product value. The airline–airline relation affects the perceived value on the produced based on its competitive advantage. Consider two competitors, where due to the additional value received from the new system, one stakeholder has a competitive advantage. This advantage can be restricted to this one stakeholder by accessibility to the system, e.g. patents or lack of knowledge. Assume that both stakeholders can purchase this system, consequently to level the playing field the other stakeholder is inclined to purchase the system as well. This is strongly related to the system properties,

- reduced accessibility to the system for competitors might increase competitive advantage and increase value

The environment might also be adapted by additional regulations or taxes increasing value for the alternative system, which might have benefits not directly perceivable by the stakeholders.

- a changed environment, e.g. regulations, might alter the perception of value

Table D.1: Decision rules for each agent.

left	0	0	0	0	1	1	1	1
0	0	0	1	1	0	0	1	1
right	0	1	0	1	0	1	0	1
Rule	0	1	1	1	1	1	1	1

Finally the value of a system might increase if the airline already possesses such a system. In particular in aviation this is the case, as shown by the success of aircraft commonality in reducing maintenance and training costs[33]. This inherently affects other markets the stakeholder might be competing in, i.e. the effect is not limited to a single neighbour.

- the stakeholder assets might change in time and alter the perception of value

The previous considerations are investigated in more detail, in particular the effect of the direct increase in system value and the increase in value due to the changing airline attributes due to commonality. Consequently the process of technology spreading is based on many factors but might be represented and studied using a cellular automaton[116, 119].

D.1 Single decision rule representation

It is assumed that the choice between available systems can be reduced as a choice for one system (1) and the rest (0). This limited evaluation has the benefit that a binary representation is sufficient to capture all possible states. Multiple alternatives can be implemented by increasing the alternative representation, however the current focus is on the emerging behaviour of a single novel technology, not on the process of deciding between multiple alternatives.

Consider for example a ring of nodes, only connected to their direct neighbours. This representation means that the state of a node is only influenced and can only influence its direct neighbours. All nodes, representing agents, are homogeneous in their decision rule. Each node is limited to two states, do not incorporate the system (0) and incorporate the new system (1). The decision rules of switching to incorporation or no incorporation are determined by the previous considerations and are summarized as follows;

- if at least one of the direct neighbours has the system, the agent is inclined to incorporate the system as well.
- if neither of the direct neighbours has incorporated the system, the agent does not incorporate the system
- if the system has been incorporated by the agent, he will continue using the system

This has been coded in the decision rules shown in Table D.1. The row labeled *left* resembles the state of the left neighbour, *0*, the state of the agent itself, *right*, the right neighbour, and *Rule* the action taken by the agent in each of the 8 possible situations. The rule can be

Table D.2: Response for $\mathcal{P} = 1$.

	Agent actions																			
step	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t
0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1
4	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	1	1
5	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	1	1	1
6	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	1	1	1	1
7	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	1	1	1	1	1
8	1	1	1	1	1	1	1	1	1	1	1	0	0	0	1	1	1	1	1	1
9	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1
10	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
11	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

read from right to left[1] as a bit string, 11111110, or 254. All possible bit strings result in 256 possible rules, and have been studied by Wolfram[195]. Although deterministic in nature the pattern emerging from the various rules is found to differ significantly. To investigate the behaviour of the above rule two initial states are investigated.

The first initial state for 20 nodes, is assumed to be 00000000000000000000. Simultaneous applying of rule 254 to all nodes results in the same state, subsequent steps do not alter this state. The emerging pattern is simple, the system remains in the complete zero state if none is assumed to adopt the new system. For the second initial state, where one — random chosen agent — adopts the system, the updating results in completely different behaviour, shown in Table D.2. The additional value due to the technology, forces the competitors to adopt the technology as well. Forcing a sure and quick spread of the technology through the grid. This illustrates the effect of the initial state on the emerging behaviour of the complete system. A small difference in initial state might result in completely different states after an infinite number of steps.

This rule is hardly representative of the real airline behaviour. As a first improvement, the decision rule is updated to represent a probability of adoption. The decision rule for situation 001 and 100 is not necessarily 1 but changes state with probability $\mathcal{P}$. As a consequence, the probability of adoption of the new technology in case one of the neighbours has the technology implemented is $\mathcal{P}(1)$. This has been represented in the first four columns of Table D.3. The probability of technology adoption might be inferred from value considerations and discrete choice analysis. This probability is an attribute of both the technology and the valuation of the stakeholder under consideration. Assuming homogeneous stakeholders and non-changing technologies, this $\mathcal{P}(1)$ is constant throughout the simulation. Due to the circular symmetry of the connectedness the location of the initial location of a single technology adoption is insignificant.

In particular the pace at which the technology is adopted by all agents is of interest. The faster the adoption of an environmentally friendly technology the better for the environment. From a manufacturer perspective, the faster the adoption of the technology, the larger the market share and the more difficult it will be for a competitor to react. As a reference

---

[1] right to left reading is employed to comply to the convention adopted by Wolfram[195].

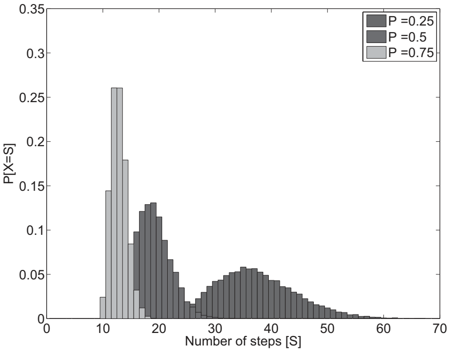


Figure D.1: Number of steps needed for reaching the all adopted state.

the number of steps for complete adoption of the technology of the previously discussed decision rule, 254, is used. The number of steps required for $\mathcal{P} = 1$ for complete technology adoption from a single adoption is $S = (N-1)/2$, where N is an odd number of stakeholders and $S = N/2$ for N an even number of stakeholders.

The other extreme occurs when the probability equals $\mathcal{P} = 0$. In this case the number of steps required for complete adoption equals $S = \infty$, that is, for only one adopter the technology is never adopted by all stakeholders. For values of probability in between these extremes the number of steps to complete adoption is likely be somewhere in between these extremes. For three values, $\mathcal{P}(1) = 0.25, 0.5, 0.75$, the number of steps to equilibrium for $10,000$ runs and 20 agents is given in Figure D.1. The number of steps required to reach the final state is given on the horizontal axis, and the number of simulations reaching this state on the vertical axis. Not only the number of steps to the full adoption state can be seen to increase with decreasing $\mathcal{P}(1)$, but also the spread in steps to convergence. This spread can be interpreted as risk. That is if the spread for complete adaption is large, also the break even point of the project shows a large spread. The large spread in break even point translates in large spread in time to project profitability and hence project risk.

For a better understanding of the cause of this spread the random decision rule is interpreted as a combination of four different rules. The original rule, 254 spreads information in both directions of the lattice/grid. Rules 252 and 238 are the right hand and left hand spreading rules respectively and rule 236 does not provide any spread at all. This is consistent with the simulation results, the larger the probability of adopting the new technology the more likely the information spreading rules are adopted, decreasing the number of steps required for complete adoption.

D.2 Network structure influence

The network employed in the previous section does not resemble the complex interconnected networks operated by airlines. Furthermore, airlines compete in multiple markets at once, with multiple airlines. This requires the investigation of the effect of the network structure on the adoption of the novel technology. Furthermore, the airline does not make

Table D.3: Probability decision rules for each agent

left	*0*	*right*	$\mathcal{P}$	236	252	238	254
0	0	0	0	0	0	0	0
0	0	1	$\mathcal{P}(1)$	0	0	1	1
0	1	0	1	1	1	1	1
0	1	1	1	1	1	1	1
1	0	0	$\mathcal{P}(1)$	0	1	0	1
1	0	1	1	1	1	1	1
1	1	0	1	1	1	1	1
1	1	1	1	1	1	1	1

a single decision for all aircraft in the fleet, i.e. for each market the aircraft is decided upon, and not as considered in the previous section on a complete fleet basis. However the adoption of a new aircraft is influenced by the composition of this fleet.

In order to represent above considerations, the technology adoption automaton is extended to a — sparse — two dimensional grid, representing the markets, designated routes, the airlines are competing in. Consider the rows to represent airlines and the columns the routes they are operating in. The values on each intersection represent which technology is incorporated by the airline on that route, i.e. which aircraft is being used, old, 0 or new 1.

D.2.1 Model implementation

Two different considerations can be employed depending on the state; 1) evaluation on a per route basis and 2) influence of the fleet composition. The *route based evaluation* is assumed based on the probability rule discussed in the previous section. Consequently, the probability of adoption of the technology is affected by the number of competitors using the technology. The *fleet based evaluation* is considered to be based on cost savings possible for commonality between aircraft. Since the airline is aware of its costs and the effect of commonality, the adoption of a novel aircraft is considered to be based on the majority rule, that is the probability of implementing a novel aircraft in a new market is increased if more novel aircraft are already employed in the fleet.

Route based evaluation

The airline investigates on a route basis if the competitors have implemented the technology. The probability of implementing the technology on route r by airline a, $\mathcal{P}(1)_{a,r}$ is based on the expected value plus the increased probability based on a competitive basis,

$$\mathcal{P}(1)_{a,r} = \mathcal{P}(1)_r + c\mathcal{P}(1)_c \tag{D.1}$$

where $\mathcal{P}(1)_r$ is determined by the value of the novel technology on the route, i.e. route specific, and $\mathcal{P}(1)_c$ is determined by the competitive value of the technology incorporation on the route,

$$\mathcal{P}(1)_c = f(N_c(1)), \tag{D.2}$$

where $N_c(1)$ is the number of competitors on the route who have adopted the technology. Finally, c determines the magnitude of the effect on the adoption probability if others have incorporated the technology. Assuming this effect to be proportional to the fraction of competitors which already implemented the technology,

$$\mathcal{P}(1)_{a,r} = \mathcal{P}(1)_r + c\frac{N_c(1)}{N_c}, \tag{D.3}$$

since $\mathcal{P}(1)_{a,r} \leq 1$, $c \in [0, 1 - \mathcal{P}(r)]$. Scaling c to α to allow for a range of $\alpha \in [0,1]$ gives

$$\mathcal{P}(1)_{a,r} = \mathcal{P}(1)_r + \frac{\alpha}{1-\mathcal{P}(1)_r}\frac{N(1)_c}{N_c} \tag{D.4}$$

This probability is used to determine the adoption of a technology on a given route.

Fleet based evaluation

A similar approach was adopted to emulate the effect of increasing technology value with increased novel technologies within the fleet. The probability of adopting an additional aircraft, although initially not adopted, is assumed to be proportional to the number of novel technologies already used on the routes r,

$$\mathcal{P}(1)_{a,f} = \beta\frac{N(1)_r}{N_r}, \tag{D.5}$$

where $\beta \in [0,1]$ can be interpreted as the benefits arising from commonality in the fleet.

Decision

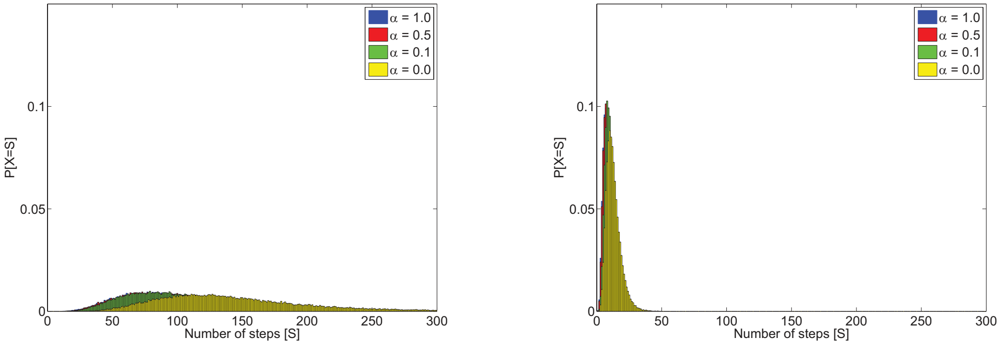
Consequently, two subsequent decisions are made; 1) a decision on a per route basis for adoption of the technology 2) a decision for adoption of the technology based on the fleet composition. That is the airline decides using rule D.4 whether it wants to implement the technology. Subsequently, a second evaluation is performed for the routes on which the technology has not been implemented based on rule D.5. Both rules determine whether the novel technology is adopted or not.

D.2.2 Results

The effect of both the value of the product, $\mathcal{P}(1)_r$, its competitive value, α, and the fleet commonality β on the number of steps required from initial adoption — the first technology appears on the network — to complete adoption — all old technologies have been replaced by novel technologies — is studied. The somewhat arbitrarily chosen network structure shown in Table D.4 is used.

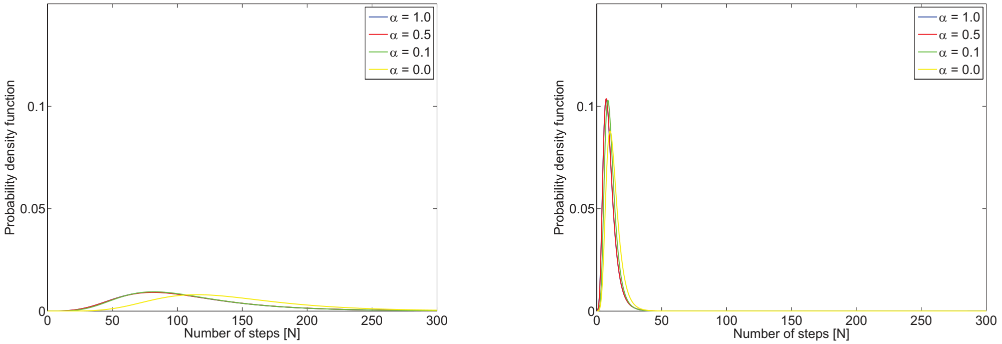
Table D.4: Assumed network

	Route ID							
	1	2	3	4	5	6	7	8
AL1	0	0	0					
AL2			0	0	0			
AL3					0	0	0	
AL4							0	0



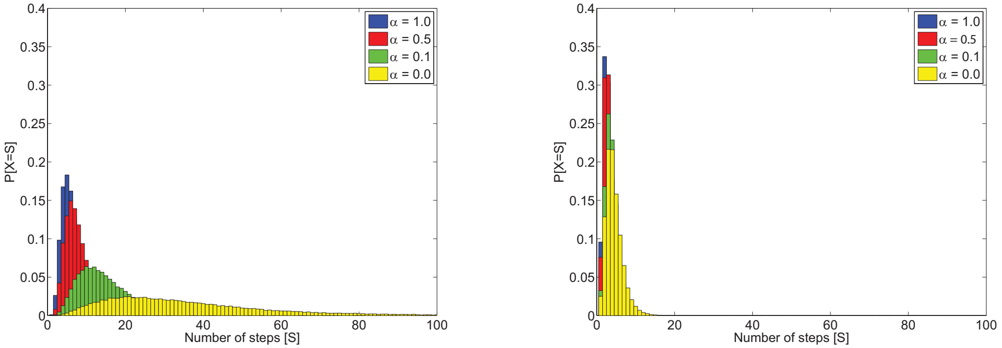
(a) $\mathcal{P}(1)_r = 0.02$ (b) $\mathcal{P}(1)_r = 0.20$

Figure D.2: Probability distribution, $\beta = 0.0$



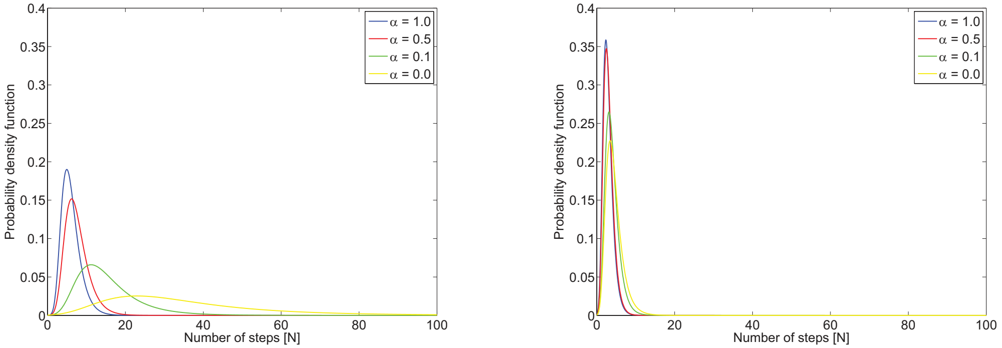
(a) $\mathcal{P}(1)_r = 0.02$ (b) $\mathcal{P}(1)_r = 0.20$

Figure D.3: GEV distribution, $\beta = 0.0$



(a) $\mathcal{P}(1)_r = 0.02$ (b) $\mathcal{P}(1)_r = 0.20$

Figure D.4: Probability distribution, $\beta = 1.0$



(a) $\mathcal{P}(1)_r = 0.02$ (b) $\mathcal{P}(1)_r = 0.20$

Figure D.5: GEV distribution, $\beta = 1.0$

Product value effect

As a reference the product value in combination with the competitive value is investigated. This entails $50,000$ runs for various values of α ranging from 0.0, non competitive value, to 1.0 full competitive value. Commonality is not considered, hence $\beta = 0.0$. The results for $\mathcal{P}(1)_r = 0.02$ and $\mathcal{P}(1)_r = 0.20$ are shown in Figure D.2. The increase in product value represented by $\mathcal{P}(1)_r$ is seen to reduce the number of steps radically, from around 120 to 20. Furthermore, the effect of α, representing competitive value affects the number of step required more drastically for the low value case than the high value case. As expected from the simple model is the spread and consequently the project risk higher for the low value case. This latter trend is more clearly seen in the general extreme value (GEV) approximations from the discrete distributions, shown in Figure D.3.

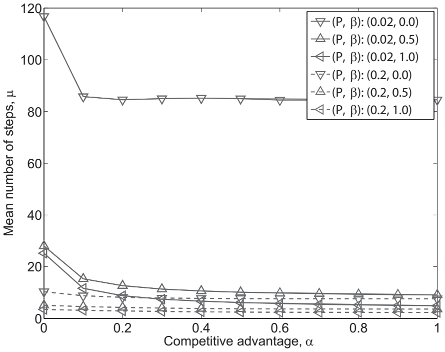


Figure D.6: Mean number of steps needed for various competition intensities.

Commonality value

The effect of commonality value for an arbitrarily chosen constant route probability of $\mathcal{P}(1)_r = 0.02$ and a fleet adoption of $\beta = 1.0$ is determined by $50,000$ simulation runs for four values of α. In addition to this, the route adoption probability is increased to $\mathcal{P}(1)_r = 0.20$ while maintaining $\beta = 1.0$. The results for both probabilities are shown in Figure D.4. For higher values of $p(1)_r$ the results show a less pronounced effect of α. That is to decrease the time to full adoption is less influenced by competitive and commonality value if the product value is already high. Comparing Figures D.2 and D.4 a general decrease in time to adoption can be seen. Note the difference in horizontal axis when comparing both figures. In order to determine the mean number of steps required from these results, the discrete distribution is assumed to be representable by a continuous probability density function of the general extreme value (GEV) type. These representations are shown in Figure D.5.

Combined effects

The mean values of all four GEV distributions, μ, supplemented by two distributions using $\beta = 0.5$, are depicted in Figure D.6. The competition effect is seen to be more pronounced for low values of α, reducing the mean number of steps from 25 to 11 by going from $\alpha = 0$ to 0.1. The effect of commonality on the other hand is even more pronounced as seen by the reduction of 120 steps to 30 steps in going from $\beta = 0.0$ to 0.5.

D.2.3 Concluding remarks

The adoption of a novel technology is consequently driven by its value in the environment, i.e. not only on a route but also in competition. The effect of competition is more pronounced if the probability of adoption is low, due to high investment costs or perceived risk. Although the model is highly simplified and uniform, the effects of competition and value are expected to represent realistic airline behaviour. Nevertheless, the probability values employed here are chosen rather arbitrarily. For useable results and technology evaluations appropriate values should be determined for the technology/ system of interest. In addition to this, the possibility of returning to the original system is not taken into account here. That is, market share captured by the new system is never lost in this simulation. This does not correspond to reality and largely affects the time to adoption for the complete technology. Furthermore, the effect of more realistic networks is still to be investigated. However, this principles demonstrated in this Appendix still apply, and this is considered more of a data than an implementation issue.

Finally, the purpose of this appendix is to illustrate the occurrence of emergence for simple behaviour rules. An from this it can be concluded that besides the general value, represented by $\mathcal{P}(1)_r$ also competition specific and commonality issues, which only occur due to the change in environment, significantly affect the adoption rate of a new technology. This illustrates the effective principle of “voluntary” adoption to spread technology through the system.

Acknowledgements

The period during which I undertook the research that led to this thesis has been an extraordinary journey. I met a lot of interesting people with equally interesting ideas and visions, without whom this thesis would not have turned out the way it is now. I would like to thank all of you personally but that would require yet another thesis altogether. Nevertheless, I would like to thank some people in particular.

Every journey has a beginning and I would like to thank the late Ronald Slingerland for providing me with the opportunity to start my PhD right after my Master's thesis assignment. Unfortunately, our cooperation ended too soon by a tragic accident. Nevertheless, our valued discussions on propeller aircraft sparked my enthusiasm for research. I would also like to thank Leo Veldhuis for his continued support and personal interest and without whom the windtunnel tests necessary for this research would not have been possible.

Fortunately, I was able to continue my research (albeit with a slightly different topic) under supervision of Michel van Tooren, who I would like to thank for providing me with the freedom to determine my own path. Our discussions have substantially contributed to the integrated nature of the framework connecting the tools in this thesis, and your enthusiasm, vision, guidance and inspiration enabled and even challenged me to go that extra mile. I am greatly indebted to you.

This research is performed within the context of the CleanEra project and I would like to thank the members of this team, Ronald, Francois, Gustavo, Hui, Marios and Michiel for their insights and sharing of ideas from the large pool of disciplines present in this team. You provided me with the broad vision required to address the challenges in design. In addition to this I would like to thank the the graduate students whom I had the opportunity to supervise, Matthijs, Mathieu, Jochem, Jasper, Tijl, Jan and Catherine. You helped me to substantiate the ideas that I did not have time to address myself.

Every PhD candidate needs a stimulating working environment to perform his research, for me this place was the DAR/SEAD research-chair. Thank you for showing me that doing a PhD-research can be much more than research. I would like to thank my roommates from over the years; Dennis, Dipanjay, and Haiqiang, for their never-ending enthusiasm on discussing ideas and Durk and Maarten in particular for proof reading large parts of my thesis and showing me that my line of reasoning wasn't always as clear and obvious as I thought it was.

I would like to thank my parents and sister for their support along the journey of life of which this PhD has only been a small (but substantial) part. Special thanks go to my dad for his invaluable help in designing the cover layout. Last but not least I would like to thank Nicole, for letting me pursue a PhD title and her support and encouragement all the way. Thank you for reminding me that there is a life next to PhD research.

It has been an interesting, and at times challenging journey, without regret for taking the first step.

About the Author

Marcel Schroijen was born on 21st of November 1981, in Heythuysen, The Netherlands. He received his high school diploma in 2000 from the Gymnasium at the Scholengemeenschap Sint Ursula, in Horn. After which he started his MSc study at the faculty of Aerospace Engineering in Delft. He received his Masters degree in June 2006 for his research on "*Propeller installation effects on directional stability and control of multiengine propeller aircraft*".

After his graduation and a short period of working as a researcher at the Faculty of Aerospace Engineering, he started his PhD under supervision of dr.ir. Ronald Slingerland on the extension of the aerodynamic model for propeller wing interaction. This research was soon integrated in the newly started CleanEra project. In this project 10 PhD students investigated methods and technologies to support and create the sustainable aircraft of the future. Within CleanEra, Marcel focussed on the requirements of this aircraft and the potential of the various technologies and methods proposed. Due to a tragic accident, dr.ir. Ronald Slingerland died in a mid air collision on the 26th of October 2007. Marcel continued the research under the supervision of Prof.dr.ir. Michel van Tooren and the focus shifted towards the design aspects of the sustainable aircraft in the context of aviation.

List of Publications

Schroijen, M.J.T. and Slingerland, R. *Propeller installation effects on multi-engine propeller aircraft directional stability and control*, 25th International Congress of the Aeronautical Sciences, Hamburg, Germany, 2006.

Schroijen, M.J.T. and Slingerland, R. *Propeller slipstream efects on directional control with one engine inoperative*, 45th AIAA Aerospace Sciences Meeting and Exhibit, 8–11 January 2007, Reno, Nevada, AIAA-2007-1046, 2007.

Schroijen, M.J.T., Veldhuis, L.L.M and Slingerland, R. *Propeller slipstream investigation using the Fokker F27 wind tunnel model with flaps deflected*, 26th International Congress of the Aeronautical Sciences, Anchorage, Alaska, 2008.

Schroijen, M.J.T. and van Tooren, M.J.L *MAV propulsion system using the Coandă effect*, 45th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, 2–5 August 2009, Denver, Colorado, AIAA-2009-4809, 2009.

Schroijen, M.J.T. and van Tooren, M.J.L *Decision support framework for future aircraft development programs*, 9th AIAA Aviation Technology Integration and Operations Conference (ATIO) 21-23 September 2009, Hilton Head, South Carolina AIAA-2009-6930, 2009.

Schroijen, M.J.T. and van Tooren, M.J.L *Environmental impact evaluation using an agent based simulation framework*, 10th AIAA Aviation Technology Integration and Operations Conference (ATIO) 13-15 September 2010, Fort Worth, Texas AIAA-2010-9332, 2010.

Schroijen, M.J.T., Veldhuis, L.L.M and Slingerland, R. *Propeller Empennage Interaction Effects on Vertical Tail Design of Multiengine Aircraft*, Journal of Aircraft Volume 47, Number 4, July–August 2010, Pages 1133–1140.

Schroijen, M.J.T., van Tooren, M.J.L, Voskuijl, M. and Curran, R.*Environmental Impact Evaluation of Aircraft at System-of-Systems Level*, 52nd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics nd Materials Conference, 4–7 April 2011, Denver Colorado, AIAA-2011-2029, 2011.