Effective industrial modeling for high-tech systems: The example of Happy Flow

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Abstract. In the design of high-tech systems like copiers, wafer steppers and televisions, modeling plays an important role. However, not all developed models are industrially successful. It would be very beneficial if guidelines were available on how to create industrially effective models that support the system architects and speed up the multi-disciplinary design of high-tech machines. In this paper, we describe a very successful industrial model in the context of the design of copiers. The model is developed for the design of the paper transport system (the mechanical layout of the paper track, the schedule of print jobs, sensors, actuators, etc.) in a multi-functional office copier. As most other activities in the printer are synchronized to the paper transport system, this design issue is at the heart of the overall design and has a major influence on the total functioning of the machine. The so-called Happy Flow model is based on kinematic modeling and its generic elements are not restricted to copiers only. Its main ideas are applicable to a much wider range of mechatronic products. It is important to learn from such instances of successful industrial models. The aim of this paper is to identify the success factors of this particular model, which forms a first step towards a more systematic method on how to construct industrial effective models.

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Introduction

In various branches of engineering, modeling plays a central role. As such, it finds also its place in the design of high-tech systems like copiers, wafer steppers and televisions. In the design of these high-tech systems multiple disciplines need to make the overall design in close co-operation. For instance, the electronic design, mechanical design and software design together need to describe a consistent, functioning machine. The designs are often made in parallel by multiple groups of people, where the communication between these groups is hampered by lack of common understanding. In addition, the complexity of a copier (typically millions of lines of code, thousands of mechanical components like frames, springs, and belts, and many motors, sensors, and printed circuit boards) give rise to many cross-disciplinary design decisions. To make a good tradeoff, the overall effect of a design decision needs to be evaluated as early as possible. This is where models come into play. On one hand models can be used to predict and evaluate the effect of possible design choices, even when the machine itself has not been built yet. In this stage models support taking design decisions. On the other hand, models can capture design decisions and can create a common understanding that bridges the gap between the disciplines involved in the design. However, even when using models, physical prototypes are essential because of the confrontation with physical reality, where overlooked issues will inevitably pop up.

Models appear in all kinds of forms; they range from simple drawings or sketches of the lay-out on blackboards to detailed models (e.g. differential equations for describing physical processes or finite state machines or automata for computer programs). In this paper we are interested in the question which properties a model should have to be effective from an industrial point of view. The goal of the Boderc project is to develop a design methodology based on multi-disciplinary modeling to predict the performance of a system in the early design phases. The aim of the methodology is to reduce the overall design effort and time and is based on the philosophy of shorter cycle times between design phases. The latter is expected to be achieved by models that can be built relatively quickly and generate reasonably accurate predictions of system behavior. To stress this point, very accurate modeling is sacrificed to reach a fast iteration through various instantiations of the model. Already the use of models has the advantage that they enable a much faster evaluation of different design options if compared to physical prototypes. The reason is that new prototypes need to be built for each new design. Through analysis of models different designs can be evaluated much faster.

Several models have been proposed in the Boderc project to support the design of a copier. The industrial partners easily used some of these models, while others did not find any employment. This indicates that there are specific properties that make a model a success in industry. To identify why certain models are embraced by industry so easily, we consider in this paper the most successful industrial model created within Boderc. This model focuses on the design of the sheet transportation system in a copier. By identifying the success factors of the model, we aim to indicate how modeling can be improved from a point of view of industrial usefulness.

The design problem

The focus in this paper is on two levels of the copier design, although they heavily interact and influence each other:

- the lay-out of the paper path,
- the scheduling of sheets.

In Figure 1 a more detailed drawing of a paper path is given.

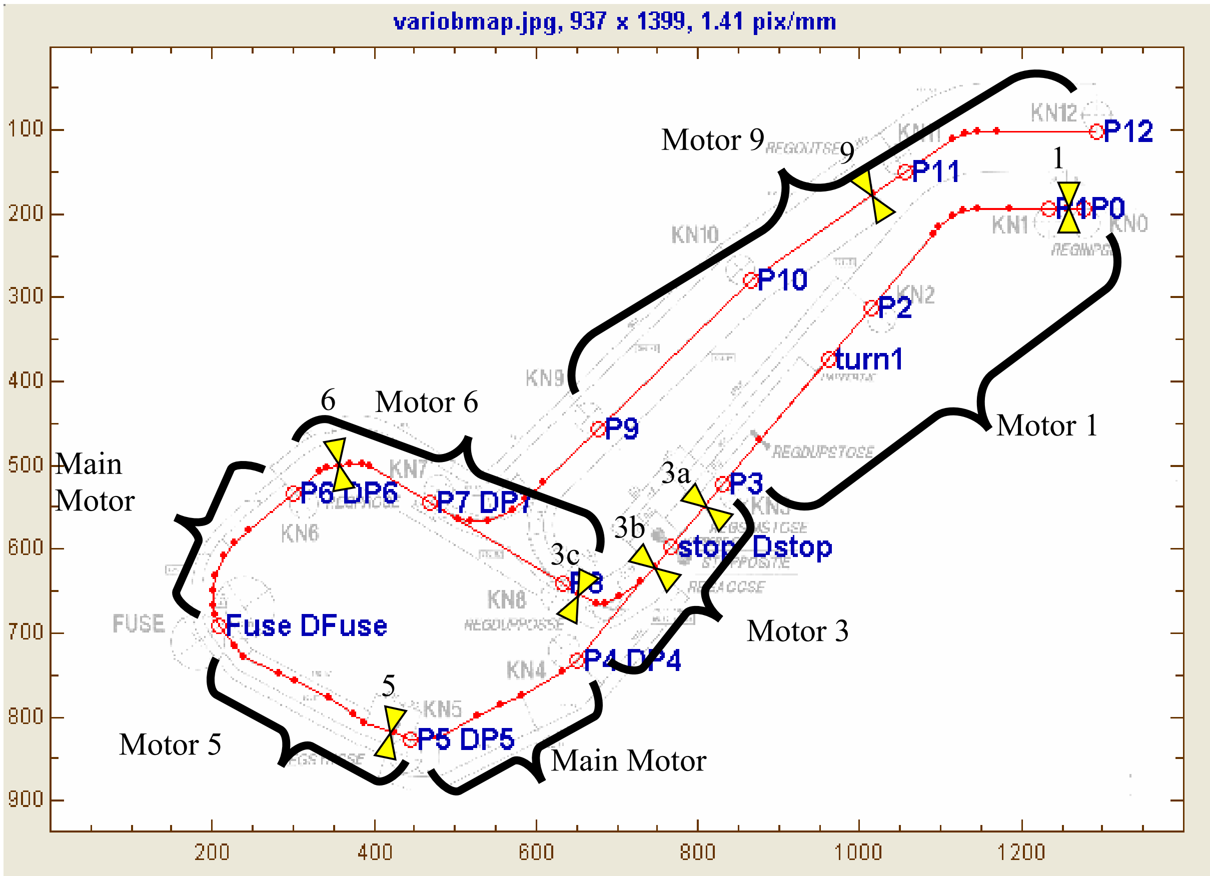


Figure 1: Paper path, with positions of the pinches, bypass and duplex loop.

The lay-out of the paper path. Several issues play a role in the design of the transportation system of the sheets in the copier. The model of the transportation system consists of several parameters of which the lay-out parameters of the track are the first that come to mind. Next to this lay-out, the drives of the sheets have to be selected, i.e. the pinches and switches/flips to direct the sheets into the right track. The pinches and switches require actuators like motors. Moreover, sensors have to be present to detect the presence of the sheets.

The lay-out of the track has to be such that some functionality of a copier is guaranteed:

- A *turn* loop has to be present to enable duplex, i.e. two-sided printing,
- *Registration and synchronization* are necessary to accurately adjust the sheet position in accordance with the images,
- The *fuse* or copy press is the location where the images are printed onto the sheets,
- A *heater* has to be present in the track such that the temperature of the sheets is increased to a desirable level for the fusing process. The track has to provide space for this.
- *Start* and *destination* of the track. The sheets have to be inserted from the paper trays at some point and have to leave the track again at the finisher. Sometimes the paper input module, the fuse and the finisher are at fixed locations due to standardization.

Within these “functional” constraints, in principle everything is possible. Although several other constraints, some based on specifications of the copier and others based on previous design experience, apply to the track. The size of the copier forms one of the most severe restrictions on the paper path, but also the maximal curvature of a curve is constrained due to bending properties of heavy sheets of paper.

The scheduling of print jobs. Given the lay-out of the track, it still has to be determined how the sheets will move through the paper path in the sense that the position and velocity profiles over time have to be determined for individual sheets (called the timing table), but also for complete print jobs. In the scheduling of a print job, the sheets motions have to be coordinated with respect to each other and for instance collisions between sheets have to be prevented. The print schedule has major implications for the total timing of the engine as most other actions in the copier are synchronized to the schedule. Indeed, from this schedule one derives the motor profiles and the requirements on motor characteristics and control algorithms, the sensor triggering and the real-time response properties of the software, the timing of the imaging process and its related subsystems and so on. Hence, the scheduling has a large impact on the total success of the copier. The scheduling is of course depending on how the mechanical lay-out is chosen and actually this lay-out imposes constraints for the schedule. For instance, if there is a certain time needed to open a closed switch/flip, this indicates that certain margins between two sheets that have to take different routes at the switch must be included in the schedule. If a desirable scheduling of the sheet flow cannot be realized guaranteeing for example a certain throughput of the machine, then an adaptation of the mechanical lay-out is necessary.

Requirements. Various key drivers and system requirements should be satisfied when designing a new system. Key drivers from the customer’s perspective are for instance minimal waiting time, ease-of-use and (re)production quality. These key drivers translate into various technical system requirements like throughput (pages per minute), position accuracy of sheets, time-to-first-print, etc. Of course, also many other (resource) constraints like power usage, cost price, size, etc, play an important role. The choice of the lay-out of the track and the scheduling have a major influence on several of these requirements:

- *Energy and power usage*: these are related to acceleration, velocity and forces required for the transportation. Energy and power usage have strict constraints; objectives related to energy labels like Energy Star play an important role, whereas maximal power usage is directly coupled to the maximal power available from a normal wall socket in the country of interest.
- *Low costs*: by using a simple concept of control, cheap and few actuators by combining drives (e.g. one motor controlling multiple pinches), the cost price of the system can be kept low.
- *Throughput and time-to-first print:* realize that certain print jobs are finished quickly.
- *Synchronization, printing accuracy and registration:* make sure that a certain reproduction quality is obtained. This requires tight synchronization and positioning of sheets and images.
- *Low complexity of control concepts:* keep the development and the size of the control software manageable.
- *Size* of the resulting copier.

Model-based design: Happy Flow

The name “Happy Flow” is based on the conscious simplification of the model, where only the desired behavior of a sheet and the ideal movements of all parts are modeled. All disturbances and variations of actual hardware performance are ignored. It is a kinematical model, where non-idealities such as friction, limited jerk of motors, and hysteresis are not taken into account.

The main goal of the Happy Flow model is to perform a quick design space exploration with respect to the job scheduling. From the insight obtained form this phase also the mechanical lay-out can be adapted in a cyclic design procedure (see the section below “Design cycle”). For the fast design space exploration the following subgoals can be distinguished:

- Easy specification of a ‘happy flow’ schedule of print jobs.
- Fast checking if for a certain happy flow, for a given paper path, for all required sheet sizes and operation modes, the design requirements like throughput and power usage are met and the constraints (safety distance between time, sufficient time to put switches in right position, etc.) are not violated.
- Verification of the robustness of the happy flow for implementation.
- Demonstration and inspection of the details of the happy flow in an easy manner, such that it can be optimized manually.
- Generation of timing tables, speed settings, and the expected times of arrival at dedicated points that will be used in the software that controls the paper path.

The prerequisite that is needed to set-up the Happy Flow model is an (initial) mechanical lay-out of the paper path including the position of pinches, switches, etc. As already mentioned before, Happy Flow is a high-level model where all sorts of low-level effects are ignored. However, the most important effects are taken into account in the model, for example critical software delays, actuation delays (e.g. solenoid delays for setting a flip), and a maximum acceleration and deceleration rate are incorporated.

Basic working of Happy Flow. The Happy Flow model started as a small and simple simulation, where logistics and timing information was combined to generate position-time diagrams for sheets in a print job. This simulation, using MatLab, extends the spreadsheet based analysis that was used in the past for these engineering problems. The availability of the input data for this simulation was also convenient for generating an animation, superimposed on a drawing of the paper path. A next step was to generate the input data for the Happy Flow model directly from available mono-disciplinary design data, such as CAD drawings. This evolution is shown in Figure 2.

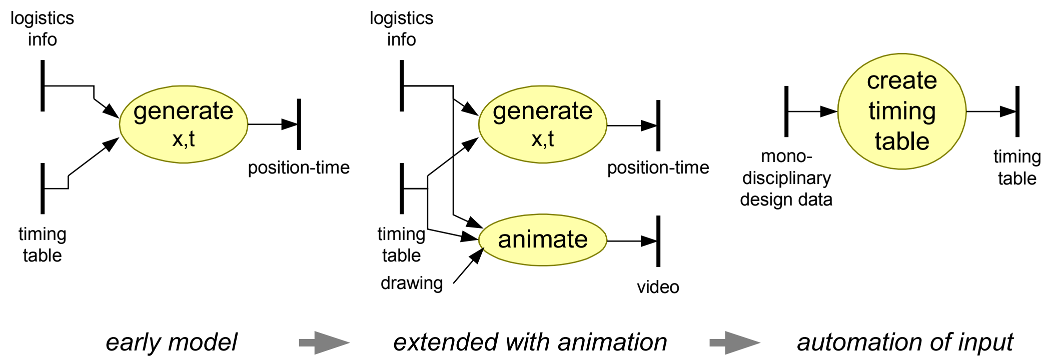
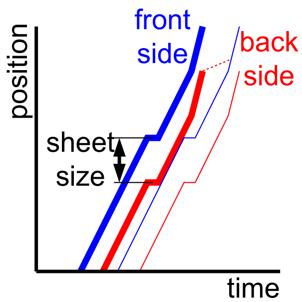


Figure 2 Incremental growth of the happy flow model.

The current Happy Flow model starts from the CAD construction drawing of the mechanical lay-out. Important registration points are indicated in the CAD drawing which are necessary to capture the mechanical lay-out in a computerized two-dimensional format. Also important points at the lay-out (like pinches, sensors, switches, etc.) are included as registration points. Typically the computerized two-dimensional information of the track consists of the coordinates of registration points and an indication how the track between them is connected, which is typically via linear interpolation. Together with individual sheet info (e.g. the length of the sheet, duplex/simplex printing, its source and destination, etc.), a 1D track is constructed. This 1D track is the one-dimensional view on the track the sheet has to travel. It consists of a concatenation of all the registration points the sheet has to pass, together with the total traveling distance. The 1D track information together with certain hardware parameters will be converted into a timing table (see Figure 3) for an individual sheet. Figure 3 shows that this information can have different representations: position-time diagram, velocity profile, or event table. Hardware parameters are for instance the relative velocity of specific pinches with respect to the fuse speed, necessary stopping times at certain positions to perform specific actions, etc. The information like the number of sheets in a job, the ordering of sheets in finisher, et cetera are collected in job info and converted into a schedule. The job schedule typically consists of the starting times of each individual sheet in the job and each sheet will follow the same timing table. For the animation typically a jpeg or bitmap picture of the mechanical lay-out (typically a simplification of the CAD drawing) is used to display the motion of the sheets through the machine. This animation is interactive and can run forward or backward at any speed. It can also animate motors and switches when they have their own specific “happy flow” specified. The animation of sheets, motors, and switches, gives good evidence that the model can work in reality. This certainly helps to detect design problems early. For example, (near) collision of sheets of paper, or unexpected delays in the paper transport are immediately visible.



	time	pos	m	v	a
sensor A	20	3	2	0.3	-0.1
pinch 1	40	9	2	0	0.1
pinch 2	50	9	2	0.3	0.1
sensor B	70	15	2	0.5	0

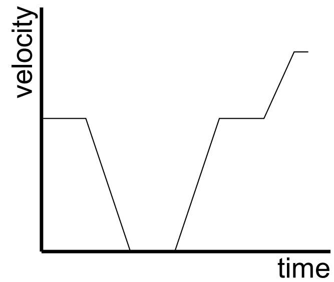


Figure 3 multiple representations used in the model: position-time diagram, timing table, and velocity profile.

The scheduling of sheets in a job. The basis of job scheduling is that the design assumes that each sheet of the same format always follows the same position-time diagram (Figure 3). The job schedule is typically based on the desired throughput (pages per minute) that has to be achieved. This throughput, the sheet format and desirable inter-sheet distance determine how fast the fuse (where the actual printing process takes place) should run. This creates a fixed rhythm of the copier in steady state operation, which can be translated to the starting times of the individual sheets in the Paper Input Module.

Animation. In the animation the timing tables are used and the 1D track developed in the model structure, i.e. the track being described on the position axis of the position/time diagrams, is mapped back to 2D and one can see the actual movement of the sheets in the print job through the paper path. As a background the CAD drawing (or a derivative of it) is used for this purpose. The animation is interactive as you can run it on any percentage of the real engine speed. Sliders and keys can be used to slow down or speed up, and you can step forward or backward to any situation, take snapshots ("photos") to illustrate documentation and make movies for presentations. Figure 4 gives an impression of what this looks like. In the upper left corner an active table of all the sheets that are currently being transported can be seen. The time until they reach the fuse for the first time (first column) and their actual position (4^{th} column), velocity (5^{th} column) and acceleration (7^{th} column) are given. The designer gets a compact overview of the paper path behavior, both visually as well as by means of specific quantified data. Both representations fit well in the engineering methods that were applied manually in the past..

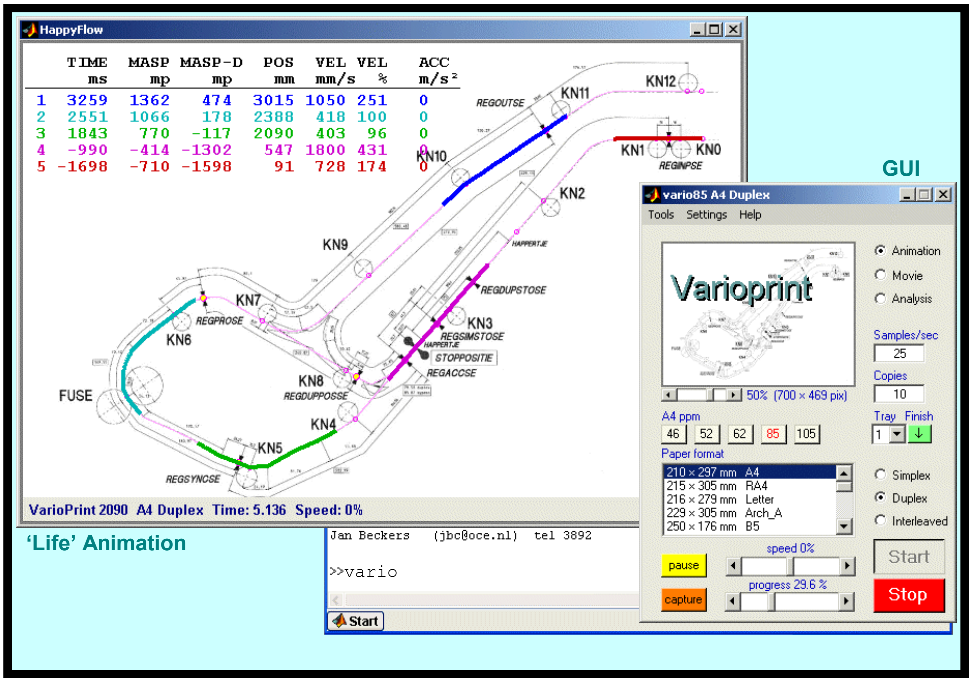


Figure 4: Impression of the Happy Flow animation

Design cycle

Typically, one designs the timing tables for the common sheets sizes A4 and A3 and for simplex and duplex and derives via minor adaptations the timing tables for other sheet sizes. If the problems cannot be solved at the level of the scheduling (timing table and job scheduling), changes in the mechanical lay-out might be necessary. Several iterations might be necessary in the design cycle as depicted below. The animation offered by the model facilitated system engineering discussions linking system level considerations, such as cost and power, to subsystem engineering considerations, in this case the kinematic properties of the paper path.

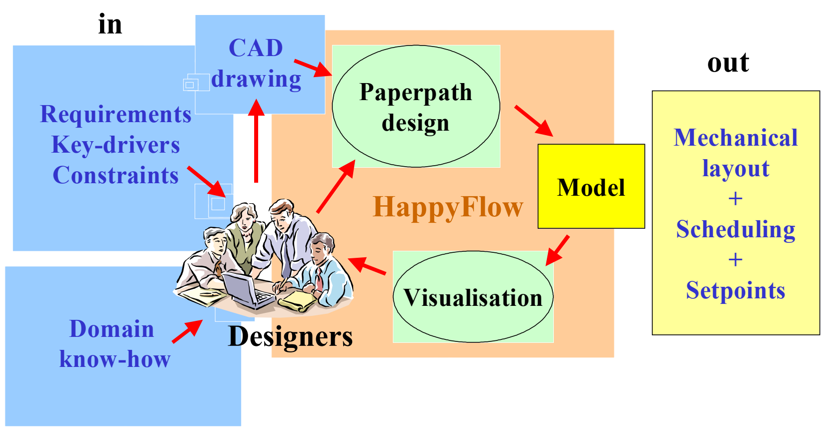


Figure 5: The Happy Flow design cycle

Industrial success factors and conclusions

Based on the success of this particular model, we will provide a list of the reasons why this model was so easily introduced in and used by industry. As indicated in the introduction, the goal of the Boderc design methodology is to enable fast model-based design space exploration in the early design space by predicting system performance. The main drivers for this Boderc goal are the *business objectives time-to-market* and *design effort/cost* while keeping *industrial constraints* like *maintainability* of a model and *human resource constraints* in mind. By human resource constraints we mean that the model should support the engineering approach used in industries. Typically this requires that the model should be *easy to learn* (low initial investment of time and effort to learn to use the model in an effective manner) and *easy to use*, properties that various academic models often lack. For short time-to-market a *short cycle time* of the application of the model is needed. This means that the model should be easy to build and should have a reasonably accurate predictive power. The right balance between accuracy and design time is important. The business objectives time-to-market and low design effort/cost are realized by sub-drivers being: using a model instead of a prototype, short calculation time for the model, stimulate cross-disciplinary communications, approach the right problem (which is crucial for the overall system design) and find relevant information in the model (and of the to-be-built system) easily. In Figure 6 we represented the above reasoning graphically. All the above mentioned drivers that realize the Boderc goal are in the end related to 12 issues that played from our perspective a role in Happy Flow's industrial success. These 12 issues are:

A. **Modular set-up.** Happy Flow has a modular set-up. The complete model and program consists of smaller parts that are connected through input-output relations (see also Figure 2). By suitable concatenation of these subprograms one obtains a high-level function that can be easily interpreted. This is important for understanding, insight and maintainability of the tool.

B. **Stepwise introduction and feedback**. Little steps in the evolution of the Happy Flow model made evaluation towards industrial practice possible and of course, the success of the individual steps led to a stepwise introduction at the copier manufacturer. Moreover, this also enables that feedback was given during the development of Happy Flow, which lead to frequent refactoring of the tool to keep its structure useful and practical for its users and purposes.

C. **Limited size.** The size of the model is limited (one thousand lines of code). This is important for understanding, insight and maintainability of the tool. The model size also has effect on speed of execution.

D. **Use of conventional paradigms.** The conventional representations of timing tables and position-time diagrams are still present in the model or can easily be generated. Hence, the outcomes of the model can still be easily communicated and transferred to all people, which are familiar with timing tables.

E. **Right representation at right place.** Several variations are used that represent the timing table for the motion on an individual sheet (see Figure 3). The representations can be converted into each other, so that for the particular purpose the "best" representation can be selected and easily generated. "The right man at the right place" so to say. This has a positive effect on speed of computation as well.

F. **Good level of abstraction.** The model has a good level of abstraction. It is not too detailed. The distance to system level key drivers like throughput, power usage, size, etc.

is not too large so that it helps to make system level trade-offs. The model is not too coarse either as it still predicts the basic timing of the sheets within reasonable accuracy. The Happy Flow model is directly connected to the design of subparts of the machines like selection of motors, real-time software, etc. Hence, on one hand it assists in predicting important system level drivers like throughput, power usage, etc, but on the other hand it also couples to mono-disciplinary (sub)design problems.

G. **Simple and fast computations.** The computations that have to be performed are very simple. This enables fast calculation of the model and thus gives answers in short time.

H. **Conceptually simple**. Happy Flow is conceptually easy to understand and as such can be used for reasoning and communication across disciplines. This supports breaking down the communication barriers, which are often present in multi-disciplinary designs.

I. **Addresses right design problem.** The model addresses an actual and current design problem. Although engineers could solve it in the past by large investments of time and effort, the introduction of Happy Flow was able to gain much in design time. It was a latent design question. Outcomes of the model are important for the overall design in the form of event or signal tables.

J. **Easy visual inspection via animation.** Visualization and animation on a picture of the mechanical lay-out (CAD drawing) makes it easy to interpret the results and makes them insightful.

K. **Data base.** In the use of Happy Flow one continuously makes assumptions for design issues that are currently unknown or not documented. By doing so one stimulates discussion and modifications in the assumptions by showing the effects via visualization. Hence, consensus is created for these assumptions and this implicit domain knowledge is somehow “documented” in the Happy Flow model. In this sense Happy Flow also has the role of a database with the latest design specs.

L. **Easy validation to reality.** It is easy to compare model output to reality (validation of model). Significant differences can be adjusted. Little deviations can be attributed to the good weather conditions under which Happy Flow works.

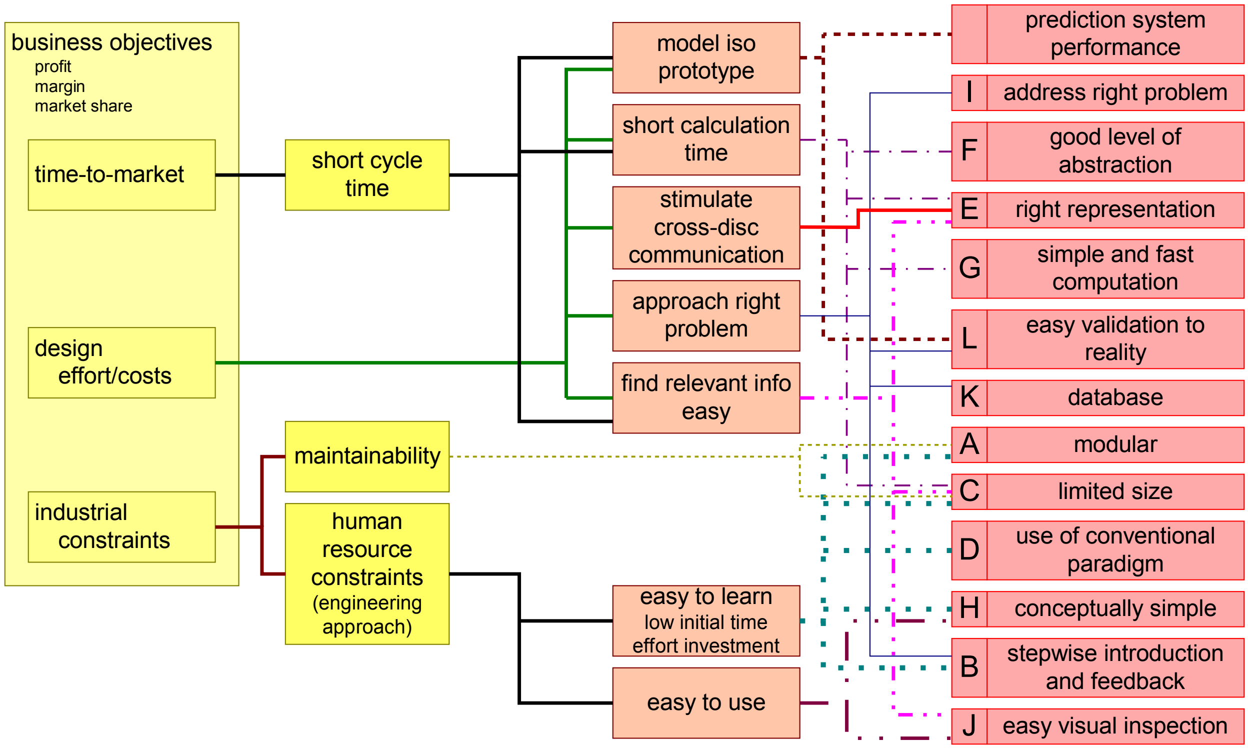


Figure 6: Overview of success factors of Happy Flow

All these factors contributed to the fact that the Happy Flow method is now used by industry and the results are promising. Engineers embrace it, explore the design space in shorter time, extract all kinds of information from it, use it for measurements and use advanced spin-off models. The designers have confidence in the model and drastic changes in the mechanical lay-out are now easily handled without hesitation even in critical phases of the development. Moreover less conservative designs are explored as well.

From an even broader, system engineering perspective, it is important to learn from such instances of successful industrial models. The identification of the success factors is a first step towards a more systematic method that gives clear guidelines on how to create industrial effective models that support the system architects and speed up the multi-disciplinary design of high-tech machines. This paper forms a first step as only one successful model is considered, but future work of the Embedded Systems Institute focuses on finding such a method.

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