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**Institutions:** New York University, University of Auckland, University of Cambridge

**Published on:** 01 Apr 2019 - Research in Engineering Design (Springer London)

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Research in Engineering Design manuscript No.  
(will be inserted by the editor)

# Modelling the planning system in design and development

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Received: date / Accepted: date

**Abstract** Engineering design and development projects involve a multitude of plans in various formats. Such documents are created, used and updated throughout a project. We argue that the interactions among plan documents, their content, their stakeholders and the planning processes can be usefully perceived as a planning system. The planning system is instrumental in coordinating a design and development project and thus strongly influences how it unfolds. In this article, a survey tool is developed to assess a planning system from its stakeholders' perspective. Results from the survey are analysed using Multiple-Domain Matrix (MDM) methodology to derive insights and suggestions for improvement. The approach is developed and demonstrated through a case study in a company that develops advanced electronic scientific instruments.

**Keywords** Planning system · Design and development · Employee survey · Multiple domain matrix · Change propagation · Case study

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## 1 Introduction

Planning in design and development is important to manage and coordinate activities, stakeholders, variables and interdependencies. Companies and the individuals within them do not rely on a single plan for a project, but use a multitude of plans. Together, the plans support all necessary aspects of planning activity and link engineering design to other considerations in a development project (Eckert and Clarkson, 2010). Although some planning documents might be finalised at the start of a project, the majority are created, managed and repeatedly updated as the project proceeds. This article considers the interaction between plans, stakeholders, the issues being planned, and the planning processes to constitute a planning system. While some aspects of a planning system might be designed in top-down fashion, other aspects emerge in response to an organisation's or project's needs. Furthermore individuals with different functional responsibility, level of management and/or relationship to the product (e.g. whether they work for an original equipment manufacturer, risk-sharing supplier or contracting company) usually perceive and conduct planning activity differently. As a result, planning involves a seemingly-chaotic jumble of documents, and people use and maintain numerous plans that are not entirely synchronised. In consequence it can be difficult to determine how a planning system is organised, whether it is suitable for purpose, and what changes might be made to improve its effectiveness.

The authors contend that planning systems are an important issue for research because they directly impact how design and development processes unfold. Explicit plans may be especially important in coordinating large-scale development projects and those with signif-

icant innovative elements, because many participants may not have prior experience of what needs to be done and what information flows need to occur. To give an example, the departments involved in a large concurrent engineering project use plans to prioritise and monitor their internal activities and deliverables. If the plans are not appropriate to purpose or not sufficiently synchronised across departments, this may contribute to some deliverables being produced at the wrong time or in the wrong sequence, or some being overlooked entirely. In consequence some workers may be overwhelmed with urgent tasks, while at the same time, others may lack the information they need to proceed. It is our view that research into planning systems could yield new insight into such coordination problems and associated inefficiencies.

The present article contributes towards this objective. An approach is introduced to elicit, visualise and analyse the design and development planning system as it exists in practice in a company. Investigation of the planning system as revealed by this approach can help to identify issues and possible improvements. The approach is demonstrated through an industry case study and opportunities for further work are suggested.

## 2 Background and review of related work

The Oxford English dictionary defines a plan as “an organised (and usually detailed) proposal according to which something is to be done” (OED, 2001). Bateman and Snell (2011) describe the activity of planning as “the conscious, systematic process of making decisions about goals and activities that an individual, group, work unit, or organisation will pursue in the future”. Planning is not an exact science, and different teams may generate very different plans for the same project (PMI, 2001).

A number of authors offer insight into plans and planning in the context of engineering design and development. In textbooks, Pahl et al (2007) for example discuss the idea of “procedural plans” for mechanical design. They describe these as “operational guidelines for action” that recommend working steps for progressing through the design process. Ulrich and Eppinger (2015) state that planning the design process involves scheduling the project tasks and determining the resource requirements.

In research journals and conferences, numerous publications report on model-based tools to support different aspects of planning in design and development considering its particular characteristics, such as iteration, uncertainty, and the complex activity networks typically involved. Some of these involve the development

of ‘optimal’ plans. For example, Eppinger et al (1994) show how dependencies in a project can be mapped in a Task Dependency Structure Matrix (DSM) to assist with planning the partitioning of work among teams working concurrently, with a view to reducing coordination needs. Browning and Eppinger (2002) develop a Monte-Carlo simulation algorithm which can be applied to a Task DSM to evaluate different sequences of attempting the tasks, and thereby arrive at a suitable plan. Other authors consider how plans change during the design process. For example, Wynn and Clarkson (2009) present a conceptual model showing how planning activity in design involves the three steps of planning, monitoring and re-planning when a plan is no longer feasible to achieve. They develop a model-based planning support method based on this concept. Karniel and Reich (2013) consider how a project activity network can be represented formally as a Petri Net and show how plan changes can be automatically merged into this network. This allows a process simulation to be appropriately updated when unplanned activities or information flows are needed during design. Shapiro et al (2016) discuss how changes to a design process plan can be represented using the Applied Signposting Model (Wynn et al, 2006) allowing their impacts to be analysed.

While these and other publications offer insight into planning the design and development process, they focus on those aspects of planning that can be represented within a single consistent activity network. They do not emphasise the real-world need to work with a multitude of interrelated and partially inconsistent planning documents, as the present article does.

### 2.1 Planning systems

Hales and Gooch (2011) write that “in a larger project, a higher level of coordination and project planning is required.” Whether by design or piecewise evolution, most organisations that develop complex products address this need with extensive planning systems. In this article the planning system is defined as follows:

*The planning system comprises all documents, information, stakeholders and processes involved in planning, and their interactions.*

In contrast with the approaches reviewed above, which focus on individual plans, some researchers have viewed the planning system more holistically. For example, in the context of engineering design, Roelofsen et al (2007) argue that planning activity can involve plans on four levels:

- 1 1. Strategic level process plans comprise generic pro-  
2 cesses and roadmaps.
- 3 2. Project level plans show only rough stages, but pro-  
4 vide a clear vision of project outcome.
- 5 3. Operational level plans focus on detailed interde-  
6 pendent activities but may not be tied to the overall  
7 outcome.
- 8 4. Action level plans focus on elementary processes.

9  
10  
11  
12 Roelofsen et al (2007) argue that the strategic plan  
13 level does not allow for case-specific planning, while  
14 planning an end-to-end project on the action level would  
15 be overwhelmingly complex. They propose that design  
16 planning should take place on the project and opera-  
17 tional levels, while continuously switching between the  
18 two. This is because project level plans are better suited  
19 for focusing on the desired project output, overall project  
20 conditions and preplanned activities, while operational  
21 level plans are more appropriate when considering the  
22 steps to be performed and allocating resources, means  
23 and methods (Roelofsen et al, 2007).

24  
25  
26 Of the many plans typically used, in most engineer-  
27 ing projects the project plan is often considered the  
28 most important from a project perspective (but not  
29 necessarily from every individual stakeholder's perspec-  
30 tive). The Project Management Institute describes a  
31 project plan as the formal approved document that is  
32 used to manage project execution (PMI, 2001). The  
33 project plan is typically laid out during the develop-  
34 ment phase and continues to evolve throughout the de-  
35 sign process (Ulrich and Eppinger, 2015).

36  
37 To summarise, it is normal for an organisation to  
38 create and use many documents as part of its planning  
39 activity. Each document offers a different perspective.  
40 At the same time, not all knowledge or information  
41 that relates to or is used while planning is explicitly  
42 represented in these documents. There may be omis-  
43 sions and inconsistencies, which may adversely impact  
44 the project and its coordination. The authors therefore  
45 contend that insight can be gained by analysing the  
46 *documented* planning system and its fitness for purpose.  
47 For the purposes of this article the documented plan-  
48 ning system is considered to be a subset of the overall  
49 planning system, and defined as follows:

50  
51  
52 *The documented planning system comprises the docu-*  
53 *ments used in planning, the content of those docu-*  
54 *ments, their stakeholders, and the interactions within*  
55 *and across these domains.*

56  
57 In the rest of this article, the terms plan and plan  
58 document are used synonymously to refer to an explicit  
59 representation of a plan.

## 2.2 Characteristics of plan documents

Within the documented planning system, individual plans  
have different characteristics that relate to how they are  
used. Plan documents can be characterised in terms of  
their content, format, and function (Eckert and Clark-  
son, 2010). These characteristics are discussed in the  
next subsections.

### 2.2.1 Plan document content

Content refers to the issues that are covered by a plan  
document. Plans often contain several forms of con-  
tent. For example, the Project Management Institute  
suggests a plethora of information that should be in-  
cluded in a project plan, and advises that subsidiary  
management plans can be used as needed to manage  
more specific project detail (PMI, 2001). Eckert and  
Clarkson (2010) introduce the concept of units of plan-  
ning to categorise the different content items that may  
be included in a plan. They discuss three basic units of  
planning:

1. Quality units of planning define milestones that the  
project and its documentation need to go through in  
order to be an auditable process. Examples include  
milestones to comply with APDQ and ISO9000.
2. Process units of planning are related to time, re-  
sources and activities. Examples include procedu-  
ral milestones, lead-times, tasks for suppliers, test  
schedules, resources, activities, and content items  
relating to firefighting schedules.
3. Product units of planning are associated with the  
product itself. Examples include content items re-  
lating to cost, bills of materials, manufacturing and  
assembly.

The actual planning content within these categories  
will vary from plan to plan based on the product, project  
and stakeholders interacting with that plan. The con-  
tent can be organised and interrelated in quite complex  
ways, depending in part on the plan's format.

### 2.2.2 Plan document format

Plans can be expressed in different formats. Gantt charts  
are common, but Eckert and Clarkson (2010) point out  
that only a small fraction of the documents used to  
support planning are expressed in this format. The for-  
mat of a planning document is impacted by the plan's  
content, but also by the tool used to create the docu-  
ment and the characteristics of the situation being  
planned. For instance, spreadsheets are conducive for fi-  
nancial plans in which cost/expenses are calculated and

managed. Precedence diagramming methods such as the Process Evaluation and Review Technique (PERT) (Pocock, 1962) and Gantt charts are useful to represent the relationships between tasks and/or their timing. Although the latter tools and especially Gantt charts are commonly used in practice, many researchers have questioned their effectiveness in the context of engineering design projects. In particular, such projects involve significant iteration (Wynn and Eckert, 2017) and dense structures of dependencies between tasks (Braha and Bar-Yam, 2007), which are both difficult to represent in PERT and Gantt charts. Additionally, because engineering design usually involves significant novelty, many tasks and their relationships will not be known at the outset of a project and are progressively clarified as that project moves forward (Albers and Braun, 2011). The difficulties of capturing all pertinent issues within a single plan format underline our motivation to consider the planning system as a whole, including multiple plans expressed in different formats.

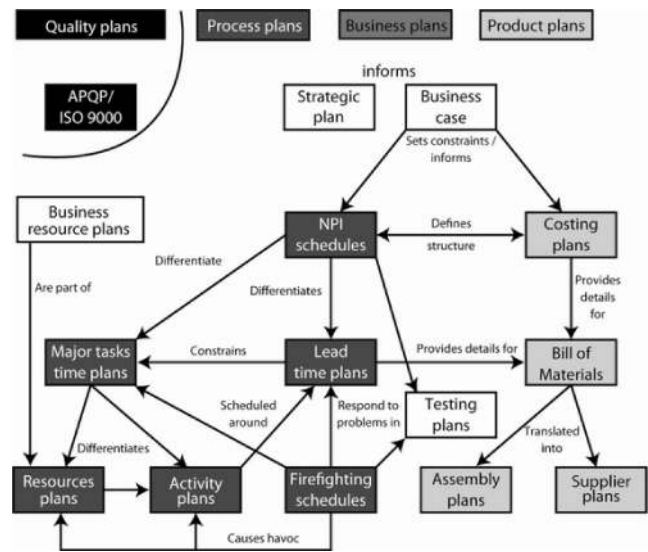
### 2.2.3 Plan function

The function of a plan describes how it is, or is intended to be, used. Klein and Miller (1999) suggest that one important function of a plan is to “develop a shared situation awareness”. They further argue that planning supports communication between team members. Eckert and Clarkson (2010) consider that plans have three main functions. First, plans that are used prescriptively show what should be done and how it should be done. They set out the sequencing and/or timing of tasks, and are typically specific and forward-looking. Second, plans that are used to define and monitor a process show what must be achieved at what point, and thereby help to identify whether work is on track. Third, plans are also arguably used to record and refer back to project events that have occurred. That is, they can be adjusted retrospectively to capture the actual development of the project, which may be useful for reflection and continuous improvement.

Plans are often multifunctional and it is not unusual for a plan’s function to change with time (Eckert and Clarkson, 2010). In addition, some plan documents are created specifically to support planning while in other instances documents created for other purposes are also used to inform and support planning (O’Donovan et al, 2005).

### 2.3 Dependencies in the planning system

There are complex interdependencies between project stakeholders, functional areas and levels of management



**Fig. 1** Types of plans and their relationship. *Figure and caption reproduced from Eckert and Clarkson (2010) with permission of Springer.*

in a typical design and development project. This is reflected in the planning system and associated planning activity.

Dependencies in the planning system are discussed by several authors. In a survey of new product management practices of small technology firms, respondents suggested that new product development plans “define the coordination between a number of people and departments—the expectations of who should be doing what, after whom” (Boag and Rinholm, 1989). In their study of new product planning principles versus practice, Feldman and Page (1984) write that product planning is inherently multilayered, cross-functional and interdisciplinary. Also highlighting the importance of dependencies in product planning, Wind (1982) argues that it should be integrated with the planning of other business functions. At the more detailed level of task planning, most model-based approaches to support planning, such as PERT and the methods discussed at the start of Section 2, emphasise the importance of dependencies or information flows between the tasks being planned.

Eckert and Clarkson (2010) consider plan dependencies based on four engineering design case studies. They developed the model shown in Figure 1 to indicate relationships between key plans they observed. It must be emphasised that Figure 1 is a simplified depiction. For example, large engineering projects can involve thousands of individuals and multiple tiers of suppliers. In this situation individualised plans will normally be maintained at every level of the hierarchy, and

1 the interdependencies between plans will often not be  
2 explicit.

3  
4 Overall, the work of Eckert and Clarkson (2010) is  
5 one of the few research articles in the engineering design  
6 journals to focus on interrelationships between plans. It  
7 provides reflections on literature and observed practice.  
8 Although Eckert and Clarkson (2010) contribute to un-  
9 derstanding the planning system in engineering design,  
10 they do not attempt to provide an approach for practi-  
11 tioners aiming to improve their planning systems. The  
12 present article aims to address this gap. We focus on  
13 the interdependencies in the planning system, because  
14 accounting for dependencies is critical to planning and  
15 scheduling content items, and is also important to en-  
16 sure that plans, content items and stakeholders remain  
17 aligned following the uncertain events and plan changes  
18 that are inevitable during a development project.  
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## 24 2.4 Summary

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27 Companies that design and develop complex products  
28 have complex planning systems. While projects may of-  
29 ten be dominated by a master project plan or equiva-  
30 lent, departments, teams and project stakeholders use  
31 additional plans that are more specific to their needs  
32 and responsibilities. These plans are often unique be-  
33 cause their content, format and function depend on  
34 how and for what purpose they are used. In addition,  
35 the plans that are used are interdependent. The depen-  
36 dencies, which are mostly implicit, reflect interactions  
37 within the planning system, impacting and intercon-  
38 necting engineering design planning and the broader  
39 development project planning. The number and variety  
40 of plans and the complexity of interactions is such that  
41 a company's planning system may appear opaque to  
42 many stakeholders. The system may not always work  
43 as intended—as Ackoff (1970) writes, planning often be-  
44 comes an irrelevant ritual that produces peace of mind,  
45 but not the desired future outcome.  
46  
47

48 The rest of this article crystallises the concept that  
49 design and development planning activity may be use-  
50 fully perceived as a system of interdependencies involv-  
51 ing plans, plan content and plan stakeholders. Browning  
52 (2001) writes that the classic approach to understand-  
53 ing complex systems is to model them. We show that  
54 modelling the documented planning system has poten-  
55 tial to improve a company's ability to manage and con-  
56 trol its design and development projects, by considering  
57 how project stakeholders manage the content they ref-  
58 erence in the plans that they use.  
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## 3 An approach to elicit and analyse the planning system

An approach was developed to model the planning system in place in a company and inform potential improvements. The approach comprises two parts. First, a Planning Management Assessment Survey Tool (PMAST) is used to elicit the planning activity of a project, team or organisation. Second, a matrix-based model is used to analyse the survey data to build an understanding of the planning system and suggest potential improvements. These two parts of the approach are described in the next subsections.

### 3.1 Planning Management Survey Assessment Tool (PMAST)

PMAST is a computerised survey tool designed to elicit the planning system as viewed by stakeholders who participate in it. Each section of PMAST is designed to elicit a key characteristic of the overall planning activity being conducted. Building on the perspective discussed in Section 2.2, this includes the plans that are used, the functions of those plans in terms of how and when they are used, and the plan content items that are referred to. Combining the responses from multiple stakeholders allows a model of a company's planning system to be developed.

The survey sections and the questions within them are arranged such that each respondent is led through progressively more detailed questions. Following recommendations of Walonick (2004), grouping questions that are similar makes the questionnaire easier to complete and the respondent more comfortable. The wordings of the questions were carefully constructed to ensure understanding and ease of answering. In addition, hyperlinks to keyword definitions are included to ensure key terms are consistently understood across respondents. The survey incorporates closed-ended questions in which the choices are predetermined, i.e. multiple-choice and matrix type questions, as well as open-ended questions which allow the participant to respond in their own words.

Structuring the survey and populating its sections with questions was an iterative process considering question generation, identification of an appropriate survey development tool and the overall survey design. Initially, over one hundred potential questions related to the design process planning activity were generated following a literature study, which is described in detail by De Lessio (2012). Selected industry interviews were undertaken to better understand the issues, during which the initial questions were refined and categorised into

Fig. 2 Overview of the Planning Management Assessment Survey Tool (PMAST)

smaller groups of related questions. When viewed together, the questions elicit key characteristics of the overall planning system. The survey was implemented in Qualtrics, which provides a web-based platform (Figure 2). In what Tukey (1977) refers to as exploratory data analysis, several industry practitioners were asked to take early versions of PMAST and provide feedback. This led to further refinement ensuring that the survey design was properly capturing the desired information. Then, pilot tests were conducted as recommended by Saunders et al (2009), with small numbers of anonymous respondents. Through this iterative development and feedback process, the survey was shown to be capable of accurately eliciting perceptions of planning practice, while the data standardisation of the survey format facilitates aggregation of the results which is necessary for the second part of the approach.

The final PMAST survey includes eight sections, of which only some are relevant to the present article. The overall organisation and content of PMAST is summarised in Table 1.

	Element A	Element B	Element C	Element D	Element E
Element A	1				
Element B		1			
Element C	1	1	1		1
Element D		1		1	
Element E	1		1		1

Fig. 3 The Dependency Structure Matrix (DSM) provides a compact representation of dense dependency structures.

### 3.2 Matrix-based model of the documented planning system

The matrix-based model is based on the Dependency Structure Matrix (DSM) and Multiple-Domain Matrix (MDM). A DSM is a square matrix in which the same elements are represented along the row and column headers (Browning, 2001). An example is shown in Figure 3. Reading across a row of the DSM shows what

**Table 1** The organisation and content of PMAST

Section	Description
Demographics	Establishes the background of the respondent and the company/department they work for. Amongst other information, this establishes data regarding functional responsibility and level of management.
Product	Establishes the characteristics of the product the respondent works on. It also categorises the product from an overall system perspective, the percentage of new design and the typical project size.
Plans used	The most critical section of the survey tool. It identifies the plans used by the survey respondent and pipes them to the remaining sections of the survey tool. The answers to this question carry through the remainder of the survey as either categories or choices in ensuing questions. This association between plans stated and specific related questions enables comprehensive elicitation of the planning system being discussed. This section also establishes the content of the plans identified, the number of projects that are simultaneously worked on and how the plans are applied to those projects.
Plan development	Identifies who creates and owns the plans that are used, and how and when they are used. For example, the respondent will indicate which of the plans they identified are used at what specific stages of the design and development process.
Plan dependencies	Identifies the individuals and functional areas of the organisation that create plans and conduct planning activity. Establishes the relationship between the individuals and functional areas involved by asking who uses the plans that are created and what dependencies the plans have with each other. Determines how and how often plans are updated and the most common reasons why they are changed.
Plan success	Identifies success criteria from a design project perspective related to the plans created and asks the respondent to rate plans' value with respect to these criteria. The section is intended to elicit opportunities for improving the planning system from the respondent's perspective.
Plan tools	Identifies the tools being used to create the plans that have been identified. In identifying the tools, the respondent is also asked how the tools are used and how satisfactory they are in meeting their planning requirements.
Design methodologies	Determines whether the respondent is aware of advanced design methodologies and tools such as DSM, and whether they currently use them or have an interest in using them. This section also determines whether design methodologies are incorporated into the planning system.

other elements the element in that row depends on, while reading down a column reveals what other elements the element in that column affects. For example, in Figure 3 element C (third column) affects element B (third column, second row) and element E (third column, last row). An MDM is similar in principle, but extends the concept by explicitly distinguishing between elements in different domains by placing them in distinct contiguous regions of the matrix headers (Lindemann et al, 2009; Bartolomei et al, 2012). An MDM can be viewed as a composite of smaller, domain-specific DSMs located along the leading diagonal, complemented by mapping matrices placed outside the leading diagonal to represent dependencies between elements across domains. Examples of MDMs are shown in figures later in this article.

The DSM and MDM approaches allows the relationships between elements of a system to be represented in a compact, visual, and analytically advantageous format that is especially useful to express a dense structure of interdependencies (Browning, 2016). In comparison to the single-domain approach of a DSM, modelling multiple domains using an MDM offers a useful advantage—a dependency between two elements in any

domain may be inferred if those elements both have a relationship with a common third element in another domain (Lindemann et al, 2009). This is of particular interest in the current article because dependencies between elements of the documented planning system are not explicit—but, we argue, implied dependencies can be extracted from the results of a PMAST survey. In particular:

- Implied dependency between plans. A potential dependency is implied if two plans share content. For example, if some tasks appear on two plan documents, change to one plan may involve the tasks, which might also need to be updated where they appear in the other plan for the two documents to remain in accord. In this hypothetical case, the co-occurrence implies a potential dependency between the plans.
- Implied dependency between plan content items. Potential dependencies between content items are implied if those content items appear together in a plan document. This may again be illustrated by example. For instance, a Gantt chart might include tasks, milestones and task due dates. In this case it



1 is likely that changing the tasks to be done would  
2 also change some of the due dates and milestones  
3 on the plan. In other words, co-occurrence on a plan  
4 implies dependence among the content items. A sim-  
5 ilar argument may be made for other situations in  
6 which several content items appear on a planning  
7 document, and we argue it can be extended to the  
8 general case.  
9

10 The co-occurrences discussed above only imply po-  
11 tential dependency, and do not ‘prove’ that the depen-  
12 dencies exist. However, some potential dependencies are  
13 more strongly implied than others. For example, if two  
14 content items co-occur in numerous plans, and this is  
15 corroborated in the responses from many survey partic-  
16 ipants, the potential dependency is more strongly im-  
17 plied than if the co-occurrence only occurred in a sin-  
18 gle plan, and was only indicated by a single survey re-  
19 sponse. The analysis later in this article considers that  
20 the more strongly a potential dependency is implied,  
21 the greater its importance in the planning system.  
22

23 To summarise, because of the concise representation  
24 and suitability for computing and depicting implied de-  
25 pendencies, the MDM approach was selected as the ba-  
26 sis for combining, visualising and analysing the survey  
27 results.  
28  
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30

### 31 3.3 Overall approach

32  
33 An overall approach for using the survey tool in con-  
34 junction with matrix-based modelling was developed.  
35 The approach was developed through a single in-depth  
36 case study and therefore reflects the needs of the com-  
37 pany that supported this research. However, a general  
38 template for analysis emerged that should be applicable  
39 to other cases as well.  
40

41 The template is depicted in Figure 4. First, inter-  
42 views are held with key stakeholders to gain initial in-  
43 sight into the organisation of the design process and the  
44 planning system used in the company. This is needed  
45 to decide on the focus of analysis and to interpret the  
46 results. Second, the PMAST survey tool is used to sys-  
47 tematically elicit knowledge about the planning system  
48 from its participants. Third, data from the completed  
49 survey is analysed using MDMs and related techniques  
50 to generate insight for management. The emphasis is  
51 placed on analysing dependencies in the planning sys-  
52 tem for the reasons discussed in Section 2.3.  
53  
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## 56 4 Case study

57  
58 The approach was developed and applied during a case  
59 study to map and analyse the documented planning  
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system in an engineering firm. This company requested  
that its identity not be revealed and therefore it is re-  
ferred to in the following narrative only as Company  
X.

### 4.1 Background to Company X

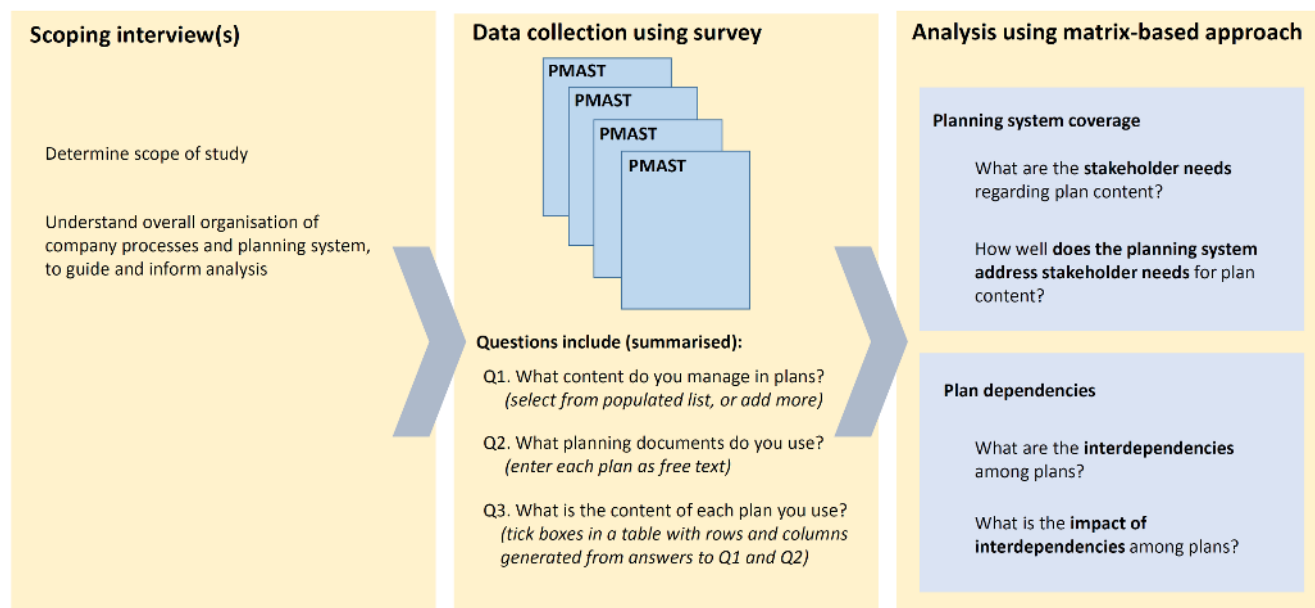
The opportunity to work with Company X arose from  
prior relationships between the company and the re-  
search group. The company designs and manufactures  
precision scientific instruments with complex designs,  
many models having purchase price in the hundreds  
of thousands of dollars. The company has more than  
25,000 employees and has facilities in more than 40  
countries. It has several product lines that each com-  
prise a family of products. Some of its development  
projects include creating new products, while others fo-  
cus on improving existing products. Many of the projects  
involve reuse of a high proportion of parts. It is common  
for personnel to work on several projects concurrently,  
and the projects can vary significantly in scope.

The research study reported here took place at a  
company facility in Germany. The following subsections  
detail the three stages of the approach as they were  
applied in this case study.

### 4.2 Scoping interview

In the first stage, the internal champion of the case  
study was interviewed to understand the company sit-  
uation and the organisation of the design and develop-  
ment processes. This took approximately 1.5 hours.

It was determined that Company X had established  
a uniform planning system for all engineering projects  
in progress using a single MS Project / Excel based  
Master Project Plan which is updated on a weekly ba-  
sis. They moved to this approach from an earlier system  
in which projects were managed independently. The  
standardised system was intended to improve coordina-  
tion in a context where many personnel have responsi-  
bilities on several projects simultaneously. In overview,  
it operates as follows. From the Master Project Plan,  
upcoming work packages are identified and distributed  
to individual engineers at the beginning of each week.  
If an engineer needs to make changes to their assigned  
work packages they must bring the issue to the atten-  
tion of their project team leader for resolution. Each  
team member is also required to report their progress  
on a weekly basis. All this feedback is aggregated into  
an updated Master Project Plan each week. New weekly  
work packages are then extracted from the Master Project



**Fig. 4** Overview of the approach. Only selected survey questions are shown.

Plan for each project team member so they can manage their responsibilities for the subsequent week.

Expectations for the research study were also discussed during the scoping interview. The champion expressed an interest in understanding how people were responding to the new system and how effective it was. Finally, the scope of the analysis was agreed. This allowed the second stage of the approach to be organised.

#### 4.3 Data collection using survey

In the second stage, fourteen employees of Company X were surveyed using PMAST to collect data on the planning system. These employees were suggested by the project champion as they were thought to be a suitable cross-section for the study. All participants in the study were members of the R&D functional team, including members of the mechanics, electronics, software and firmware groups. In terms of their positions in the organisation, eleven participants self-identified as staff, one as a supervisor, one as a manager, and one as senior management. In terms of roles, nine identified themselves as in an engineering role, three as project management, one as R&D, and one as outsourced personnel. This is summarised in Table 2. Two product lines were represented. Some respondents worked within one product line while others had responsibilities in both at the same time. Only one respondent reporting working on a single project at the time of the survey. Seven reported that they were working on 2 or 3 projects simultaneously; another 3 were working on 4 or 5 projects; another 3 on 6-10 projects; and one reported that they

were contributing to more than 10 projects at the same time.

The survey was completed in a series of individual sessions. There was no written brief; instead, the first author was present at every session to verbally introduce the research and answer questions that arose. During each session, the respondent was asked to complete the PMAST survey and verbally prompted by the researcher to discuss the reasoning behind their answers. This approach helped to ensure respondents had a consistent understanding of the concepts covered by the survey. It also helped the researcher to appreciate the company context, which was important to provide direction for the matrix modelling. Each session took between 1 and 3 hours depending on the discussion, and was audio-recorded for future reference.

#### 4.4 Analysis

In the third stage, the data from the 14 completed surveys were combined and analysed to draw insights regarding the planning system in Company X.

The survey provides a detailed data set and many analyses are possible. This article focuses on two issues: coverage of the documented planning system and implied dependencies between plans in the documented planning system. These were both revealed to be important during the scoping interview and discussions. Analyses of these issues are described in Sections 4.5 and 4.6 respectively.

**Table 2** Participants in the study

#	Department	Level	Responsibility (as described by participant)
1	Engineering	Senior management	Senior Director R&D
2	Engineering	Management	Department Manager R&D
3	R&D	Supervisor	Team Leader R&D
4	R&D Project Management	Staff	Sub-project leader, Software & Firmware
5	Engineering	Staff	Electronics, Current sources, Input devices
6	Engineering	Staff	Electrical engineer
7	Engineering	Staff	Electronics engineer and project leader
8	Engineering	Staff	Designing electronics
9	R&D	Staff	Software development
10	Engineering	Staff	Mechanical design
11	Outsourced personnel	Staff	CE conformity and CSA approvals
12	Project management	Staff	Subproject leader and contributing team member
13	Engineering	Staff	Third-party supplier contact person
14	Project management	Staff	Project leader

## 4.5 Analysis of documented planning system coverage

### 4.5.1 Stakeholder needs regarding plan content

Although it may arguably be desirable to include all interdependent content items in a single plan so that all relevant issues can be considered together, there is also a pragmatic need to limit content to keep each plan and its format manageable. Because Company X's planning system revolves around a Master Project Plan from which individual plans are derived, the content of this plan is especially important in the overall system. It was therefore decided to begin the analysis by determining which content items should ideally be included in the Master Project Plan considering the needs expressed by stakeholders.

#### Construction of a Planning System MDM

To address the objective stated above, a Planning System MDM was constructed as follows. During the survey, respondents were asked which content items they manage using plans. As shown in Figure 6, the plan content items were selected from a prepopulated list which was developed and validated through the iterative feedback process explained in Section 3.1. Respondents were able to add further items if desired. The results of each respondent's answer to this question were used to fill Mapping A in Figure 5. In particular, if a respondent indicated that they manage a particular content item using plans, a 1 is entered in the corresponding cell of Mapping A. Otherwise, the cell is empty.

To populate DSM B in Figure 5, Field A was analysed to determine Commonality Values and Importance Values. First, to generate the Commonality Values, every content item revealed by the survey was compared to every other content item to determine how many of the respondents use both items. For example, when

comparing tasks and milestones, respondents 1, 2, 3, 5, 6, 8, 10, 11, 12, 13 and 14 indicated that they refer to both content items in the plans they use. Because there are 11 respondents in this list, the Commonality Value for the tasks-milestones pair is 11. Second, to generate the Importance Value associated with each content item, the respondents who state they refer to that item were counted. Once calculated, the Commonality Values were used to populate DSM B in Figure 5. DSM B (and hence Mapping A) is sequenced so that the content items appear in decreasing order of Importance Value, which is shown in the column at the far-right of Figure 5.

#### Analysis and insights

DSM B in Figure 5 provides insight into how content items should be clustered across plans. In particular, content item pairs with high Commonality Values should be prioritised for inclusion in the same plans. Although content item pairs with a low Commonality Value might be individually important, because few people use both content items together it is reasonable to assume that they do not need to be considered together during a typical planning activity. These content items could be clustered into separate plans, which is desirable to reduce the complexity of the plan documents.

To recap, the objective of this subsection was to identify the 'ideal' set of content items to include in the Master Project Plan. Because other plans are derived from the Master Project Plan, the content items with high Importance Values should be included. Content items that are strongly clustered by Commonality Value should also be included, to ensure that the implied dependencies among those items are appropriately accounted for before propagating the planning decisions to individual engineers each week.



Do you create/use a plan to manage the following **planning items**? (please select all that apply)

<input checked="" type="checkbox"/> Milestones	<input type="checkbox"/> Quality	<input type="checkbox"/> Profit
<input checked="" type="checkbox"/> Lead-times	<input checked="" type="checkbox"/> Risk Management	<input type="checkbox"/> Distribution
<input checked="" type="checkbox"/> Freeze dates	<input checked="" type="checkbox"/> Manufacturing	<input type="checkbox"/> Activities
<input type="checkbox"/> Tasks	<input type="checkbox"/> Sales	<input type="checkbox"/> Process
<input type="checkbox"/> Test Schedules	<input type="checkbox"/> Advertising	<input type="checkbox"/> Communication
<input type="checkbox"/> Resources	<input type="checkbox"/> Product	<input type="checkbox"/> Other <input type="text"/>
<input type="checkbox"/> Costs	<input type="checkbox"/> Design	<input type="checkbox"/> Other <input type="text"/>
<input type="checkbox"/> Bill of Materials	<input type="checkbox"/> Revenue	<input type="checkbox"/> Other <input type="text"/>
<input type="checkbox"/> Assembly	<input type="checkbox"/> Pricing	<input type="checkbox"/> Other <input type="text"/>

**Fig. 6** The survey question used to elicit the plan content items used by each respondent.

Moving down the list of Importance Values, lead times, resources, assembly, design and bill of materials all have relatively high Importance Values of 7 or 8. They could thus also be candidates for inclusion in the Master Project Plan. However, inspection of DSM B reveals that only resources has high Commonality Values (of 7 or 8) with all five of the content items identified for inclusion in the previous paragraph. In contrast, lead times has the same Importance Value as resources, has high Commonality Value with only three content items in the original group, while the other three have high Commonality Values with only two in the original group. Based on these observations, resources might be considered for inclusion in the ideal Master Project Plan. The other four content items could perhaps be managed using a different plan, to avoid creating a Master Project Plan that would be unwieldy and difficult to maintain.

Overall, this subsection demonstrates how a Planning System MDM can help to facilitate consideration of stakeholder needs regarding plan content. With respect to the Master Project Plan in Company X, Importance Values were used to prioritise planning items for inclusion considering the number of stakeholders who interact with them. Consideration of Commonality Values indicated clusters of potentially-interacting content and thus helped to delineate important items that should be considered together in the Master Project Plan from similarly-important items that might be partitioned into a separate plan, in order to keep the complexity of the document under control.

*4.5.2 Evaluation of the Master Project Plan against stakeholder needs*

Having considered the ‘ideal’ content for the Master Project Plan, the second step of the analysis was to compare this against its actual content as revealed by the survey. The objective was to identify any points

of difference and consider whether modifications to the Master Project Plan should be recommended to address them.

**Construction of a Planning System MDM**

A second variant of the Planning System MDM was developed to undertake this analysis. The MDM, shown in Figure 7, was constructed by incorporating information from additional survey questions. In the first of these questions, the respondent was asked to name the most important plans they use (Figure 8). Every respondent included the Master Project Plan in their response. A maximum of five plans could be entered at this stage due to limitations of the survey tool. After providing this information, the next survey question asked the respondent to indicate which of the previously-mentioned content items appear in each of the plans that was named (Figure 9).

The content items that each respondent stated they reference in the Master Project Plan only were placed in Mapping A of Figure 7. Commonality Values considering only the Master Project Plan were then calculated considering Mapping A and placed in DSM B while maintaining the highlighted blocks, row/column sequence and cluster boundaries shown in Figure 5. Finally, the values in each cell in DSM B of Figure 7 were subtracted from the values in the corresponding cells of Figure 5. A score of zero in Figure 7 therefore implies that the Master Project Plan adequately provides the corresponding dependency-related plan content the survey respondents need. A score greater than zero indicates that respondents may need to refer to other plans to find information about the implied dependencies between content items. The highlighted blocks indicate the overall Commonality Value of each implied dependency, as per Figure 5.

**Analysis and insights**

Analysis began by focusing on the content items having high Importance Values and associated with high Commonality Values, in the first (topmost) cluster of

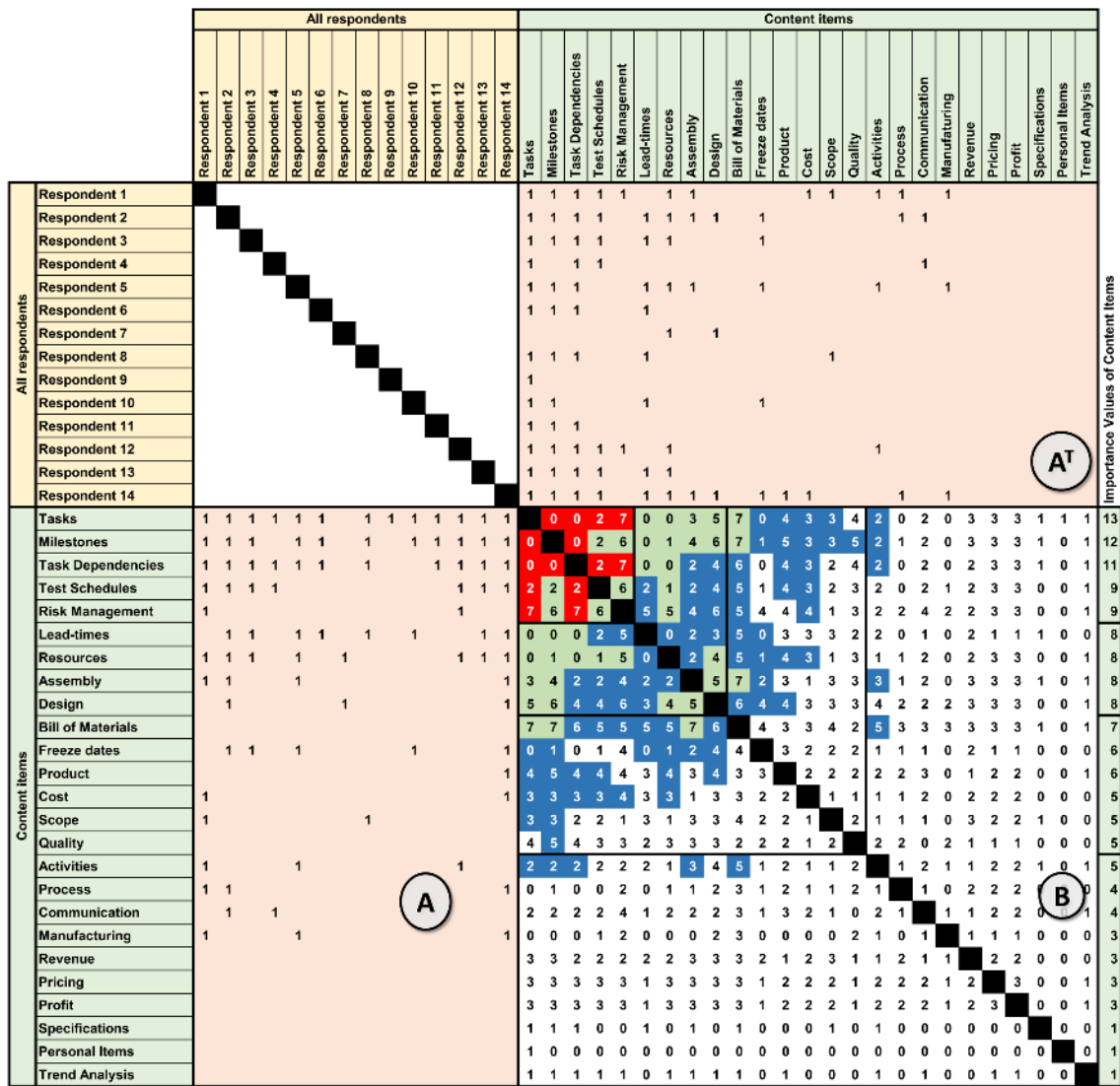


Fig. 7 A variant of the Planning System MDM created to compare content of the Master Project Plan against stakeholder needs. A large positive number in DSM B implies that the corresponding pair of content items are both used by many survey respondents, but few respondents find both content items in the Master Project Plan. The sequence of items, cell colours and clusters are the same as in Figure 5.

Please name up to the five most important **planning document(s)** you use/reference for planning

(most important)

(least important)

Fig. 8 The survey question used to elicit the most important planning documents from each respondent's viewpoint.

What is the [content](#) of the plan(s) you use? (please select all that apply)

	Milestones	Lead-times	Freeze dates	Risk Management	Manufacturing
Project master plan	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Calendar	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Bill of Materials	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>

**Fig. 9** The survey question used to elicit which plan content items are used in which plans by each respondent. This question is generated dynamically by the survey tool; the rows and columns of the table are determined by the same respondent's answers to the earlier questions shown in figures 6 and 8.

DSM B in Figure 7. The data indicate that the Master Project Plan in Company X adequately addresses stakeholder needs regarding the high Commonality Values among tasks, milestones, and task dependencies. Figure 7 also shows that high Commonality Values between test schedules and the aforementioned content items are mostly handled by the Master Project Plan. On the other hand, the Master Project Plan does not reflect the high Commonality Values between risk management content and other items in the topmost cluster, and by a significant margin. The interviewees indicated they conduct a separate risk management analysis for each project, but it is not incorporated into the Master Project Plan. It was therefore recommended that Company X should consider incorporating risk management considerations into the Master Project Plan.

Moving on to consider the second-from-topmost cluster of content items in Figure 7, the data indicate that the Master Project Plan meets stakeholder needs regarding Commonality Values for only some of the content items on this tier, namely lead times and resources. Regarding dependencies that involve the other content items on this tier, namely assembly, design, and bill of materials, the higher values in DSM B of Figure 7 indicate that the Master Project Plan does not meet the needs of many of the respondents. This suggests that Company X should consider including these content items in the Master Project Plan or, if the content is already included, should investigate why the participants stated they do not find that content in the plan. It could also indicate instances where the content item does not fit into the format of the Master Project Plan or is managed in some other way. This is the case, for example, with design-related content items, for which several of the interviewees mentioned schematic diagrams are used.

#### 4.5.3 Comparison of the entire documented planning system against stakeholder needs

The previous section identified dependencies among plan content that are strongly implied in the survey results, but which are not found in the Master Project Plan.

Information about these dependencies must be managed in other parts of the planning system, i.e., in (1) other plans; or (2) other documents they do not consider to be plans, or (3) undocumented sources such as discussions, meetings, e-mails and telephone calls. The third step in the analysis focused on the degree to which the entire documented planning system satisfies stakeholder needs, in order to identify possible omissions.

#### Construction of a Planning System MDM

Figure 10 was constructed using the same technique as Figure 7 to analyse the plan content not just for the Master Project Plan, but considering all of the plans utilised by the respondents.

#### Analysis and insights

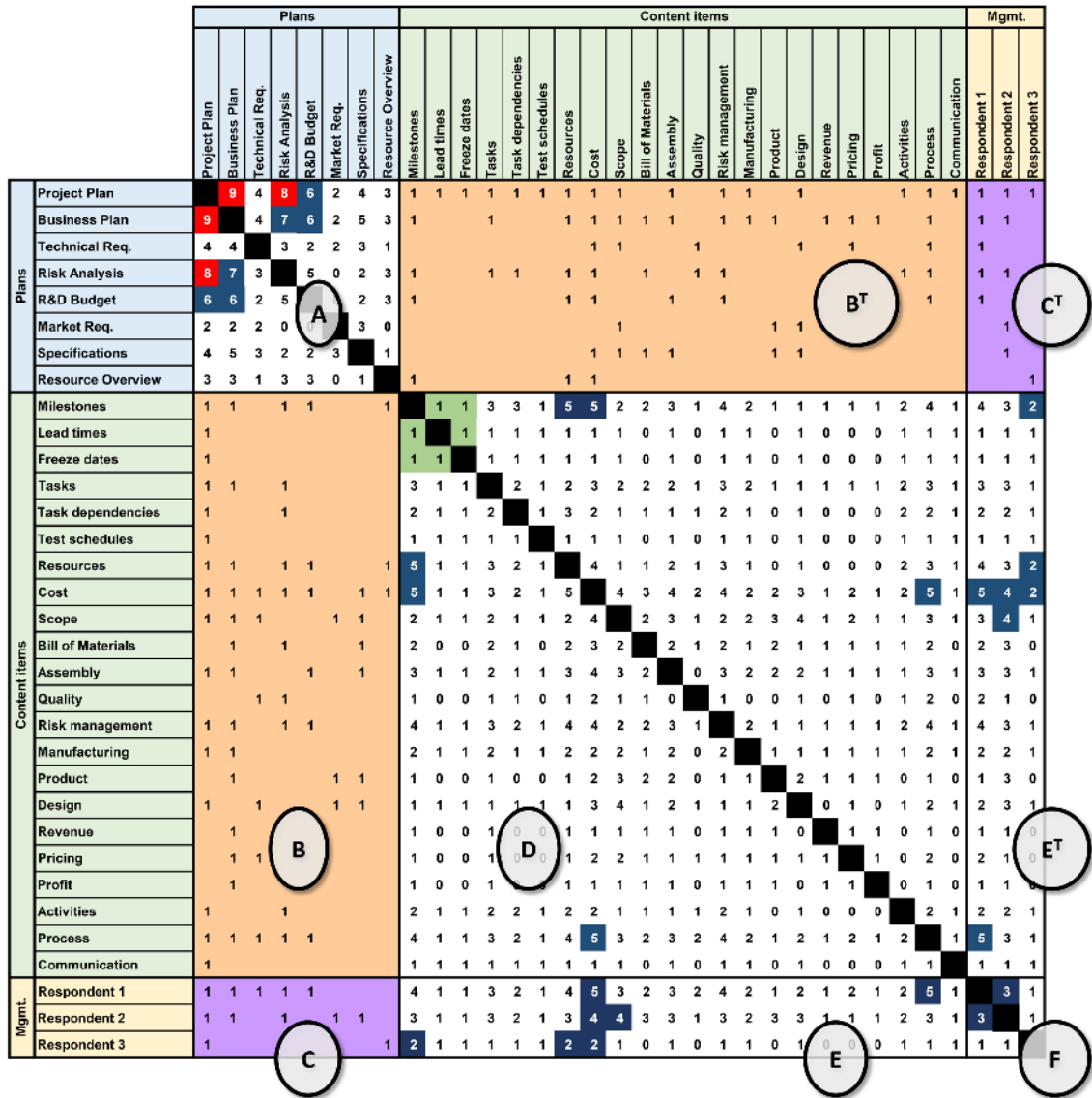
Figure 10 reveals that the co-occurrences in the documented planning system considering all plans combined come much closer to reflecting the implied dependencies among content items than the Master Project Plan does alone. Instances where the co-occurrences fall short of the implied dependencies indicate where the documented planning system may not currently meet stakeholder needs. Of particular note is the limited coverage of implied dependencies between content items relating to design/bill of materials and other plan content items that have Importance Value of 7 or greater.

#### 4.6 Analysis of implied dependencies between plans

Having shown how the approach can be used to gain insight into coverage of implied content item dependencies by the documented planning system, this section focuses on the implied dependency between the plan documents themselves. This analysis was motivated by the observation that, in many situations, unintegrated but interdependent representations of how work gets done are maintained by the process participants (Eckert et al, 2017). In the context of planning systems, it is common for multiple plans to contain overlapping content (Eckert and Clarkson, 2010, see Section 2.3). As discussed in Section 1, if improperly managed such plan content dependencies may cause conflicting priorities and coordination issues. For example, changes







**Fig. 11** Variant of the Planning System MDM highlighting implied interdependencies in the planning system used in Company X, as perceived by management employees. *Key: plans are shown in the top/left section of the MDM; content items are shown in the central part of the MDM; survey respondents from the management team are shown in the lower/right part of the MDM. The meanings of highlighted cells and labels are explained in the text. Cells obscured by annotations are empty or have value 0.*

and survey respondents from the management team. It was constructed as follows.

First, the raw data from the surveys were manually aggregated to identify the row and column headers for the matrix and to construct Mappings B and C in Figure 11. For Mapping B, if one or more respondents stated they refer to a particular content item within a particular plan, a mark is shown in the corresponding cell of the mapping matrix. Mapping B therefore indicates the specific content items that coincide on a particular plan considering the viewpoints of all management respondents. Mapping C shows the plans which each respondent indicated they interact with. It can

thus be used to determine which plans respondents use in common. For instance comparing Respondent 1 and Respondent 2, Mapping C indicates that they share use of the Project Plan, Business Plan and Risk Analysis.

Second, Mappings B and C were used to compute all other fields of Figure 11. DSM A is computed from Mapping B to reveal the overlap between plans as used by the management team. For example, it indicates that nine content items are included in both the Project Plan and the Business Plan. Mapping E was populated from Mappings B and C together, considering how many of the plans used by the same respondent contained the same content items. For example, it shows that four of

the plans used by Respondent 1 include milestones. The plans in question can be identified considering Mappings B and C, and in this case are the Project Plan, Business Plan, Risk Analysis and R&D Budget. DSM D indicates the number of times that each content item pair appears in the same plan. This is computed from Mapping B. Finally, DSM F shows how many plans are used in common by each pair of respondents. This is computed from Mapping C.

#### Analysis and insights

Detailed consideration of Figure 11 yielded the following insights. First, DSM A indicates that the Project Plan has high implied interdependencies with the Business Plan and the Risk Analysis, as represented by values of 8 or 9 highlighted in red in DSM A, and to a lesser extent with the R&D Budget. Although unsurprising, this does highlight that care needs to be taken to propagate changes from any one of these plans to the others in the cluster. This is especially true for the Project Plan and the Business Plan which are produced by different functional areas, and in the case of Company X implies that it may be worth expanding the Project Plan's use to include the business function. The observation also supports the case made earlier for incorporating the risk management content into the Project Plan if possible.

Second, certain content item pairs stand out as appearing frequently together in the same plans. In particular, Mapping B of Figure 11 indicates that milestones are coupled with resources and cost in 5 plans, while process is also coupled with cost in 5 plans. These strong couplings are also highlighted in DSM D. It seems reasonable that these particular content items are coupled. However, it may be appropriate to consider whether it is necessary for multiple plans to represent the couplings.

Third, considering the nature of planning activity and the insights from earlier sections it might be expected that milestones, lead-times and freeze dates should frequently appear together in the same plans. That is not the case here, as highlighted in green at the top-left of DSM D in Figure 11. This could be explained by the dominance of the Master Project Plan in the documented planning system analysed. In Company X, while milestones are brought into multiple plans for potentially different reasons, lead times and freeze dates are typically only found in the Master Project Plan, from the management perspective.

Fourth, the maximum number of plans that are shared among any two Management respondents is three. These implied dependencies are highlighted in DSM F of Figure 11. This raises the question of why members of the same management team are using so many different plans particularly considering that the planning sys-

tem is dominated by a single Master Project Plan. This could indicate a potential area for concern if there were a significant amount of content shared between all the plans used. While the data show that is not the case for Company X, there are still instances where changes to one plan could impact other plans that are used by different individuals.

Finally, Mapping E of Figure 11 indicates situations where certain content items have significant impact on a particular respondent's planning activity (highlighted cells in Mapping E). This may be useful to suggest who should be notified when a certain content item is updated.

#### 4.6.2 Implied dependency between plans from the staff perspective

To complete the study a similar analysis was performed considering only the responses from Staff.

#### Construction of a Planning System MDM

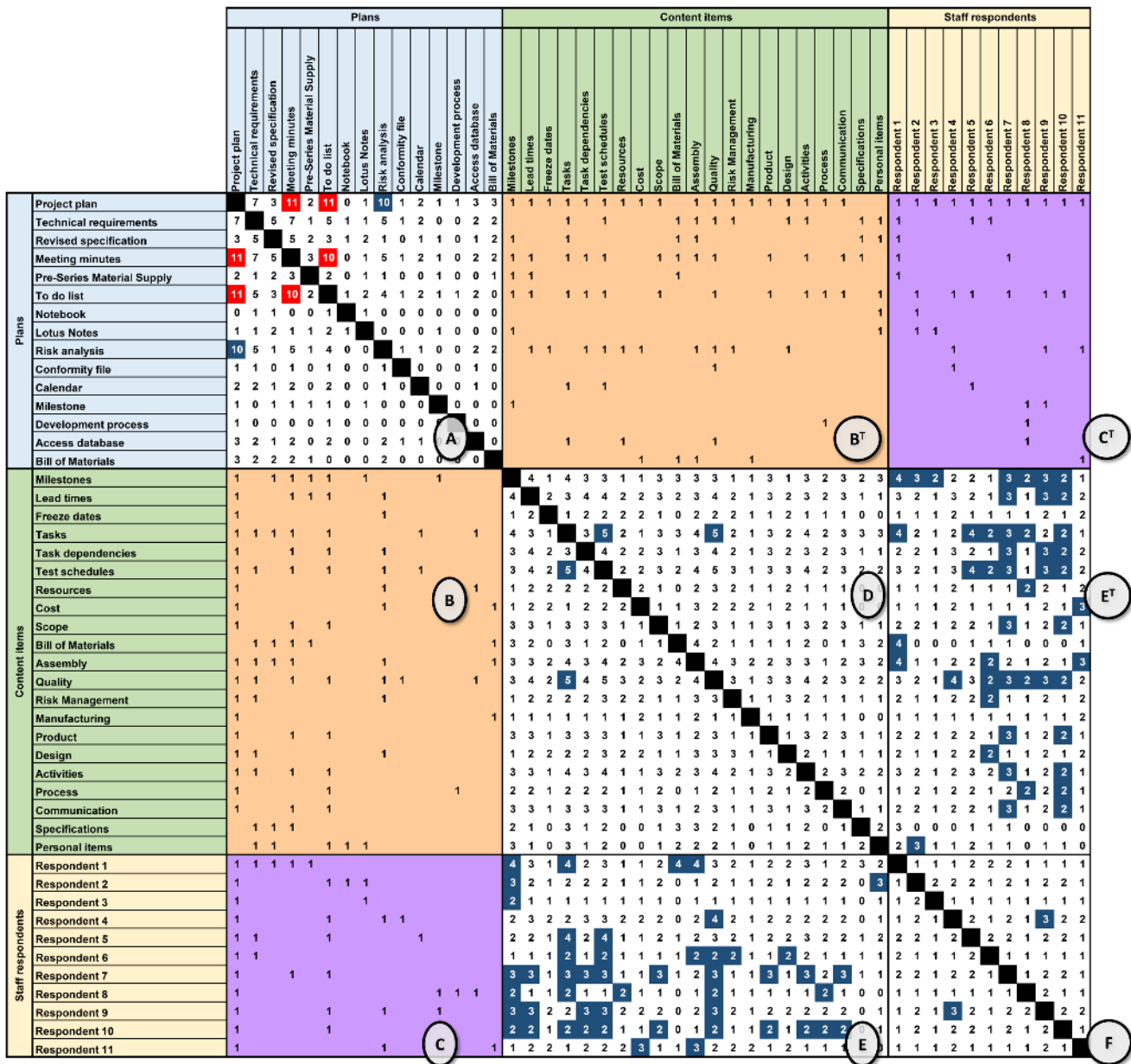
Figure 12 is equivalent to Figure 11 in construction, but focuses on the documented planning system as viewed by the staff respondents. To construct this matrix some aggregation of data was required to account for differences in nomenclature. In particular, all forms of the Master Project Plan mentioned by the respondents were grouped together under the heading Project Plan. In addition any plans that shared the same name in the survey results were also grouped together, even though they may refer to different documents created by different individuals.

#### Analysis and insights

Figure 12 reveals that from the staff perspective the Master Project Plan has high implied interdependencies with both Meeting Minutes and To Do Lists (values of 10 and 11 highlighted in red in DSM A of Figure 12). There is also a strong indication of dependency between Meeting Minutes and To Do List. These observations are in alignment with comments during the survey sessions that many staff members create simpler individual plans based on the Master Project Plan.

Second, there is high implied dependency between the Master Project Plan and the array of risk-related plans that have been grouped together as Risk analysis (values of 10 highlighted in blue in DSM A of Figure 12). To recap, it had been noted during the survey session discussions that risk analysis is often done independently from generating the Master Project Plan. Figure 12 reinforces the insight from earlier sections that the Risk Analysis content should be considered for inclusion in the Master Project Plan.

Third, tasks and test schedule content appear more frequently in the same plans than any other content



**Fig. 12** Variant of the Planning System MDM highlighting redundancy of plans used in Company X, as perceived by non-management employees. The key for this figure is the same as for Figure 11.

item pair, except for tasks and quality (values of 5 highlighted in DSM D of Figure 12). This is not surprising considering that test schedules are often dependent on the completion of specific tasks. What is surprising, however, is that other related content items such as task dependencies and milestones do not appear in the same cluster. It is also notable that quality is often coupled with tasks, considering that the former did not appear extremely frequently when respondents were asked to state what content they reference (as per the relatively low Importance Value for quality, which is shown in Figure 5). While quality content is not currently included

in the Master Project Plan this suggests that the staff who do refer to it are incorporating it into a number of other plans. This suggests that quality-related content should be considered for incorporation into the Master Project Plan.

Fourth and finally, Mapping E of Figure 12 indicates the content items that are most common across the set of plans that are used by each staff respondent. The highlighted cells indicate the content item(s) shared across the largest number of plans used by each individual. Such commonality might be expected if multiple plans were derived from the same information source.

1 That is not the case here where only the content items  
2 of milestones, tasks, test schedules and quality are shared  
3 across a number of the plans used by the same individ-  
4 ual. Instead, insight into the planning system gained  
5 from the survey session discussions suggests that this  
6 category indicates a matter of personal preference re-  
7 garding the way individuals create and use plans. It was  
8 concluded that this is a desirable feature of the current  
9 planning system, showing that it gives individual stake-  
10 holders the ability to focus on content most important  
11 to them while still having access to all the content they  
12 may need at various points in the project.

#### 16 4.7 Closure of the case study

17 After completing analysis of Company X's planning sys-  
18 tem, a detailed report on the insights and recommenda-  
19 tions was created. Additional to the detailed analysis,  
20 the report included a summary of key points relating  
21 to the Master Project Plan, which as mentioned in Sec-  
22 tion 4.2 was the main topic of interest for the project  
23 champion. These points included:

- 24 – Risk Management: As discussed in Sections 4.5.1,  
25 4.6.1 and 4.6.2, risk management content was used  
26 by many participants but dependencies between risk  
27 information and other content were not adequately  
28 accounted for in the Master Project Plan. At least  
29 one individual stated verbally that lack of coordi-  
30 nation between the Master Project Plan and Risk  
31 Management Plans was perceived as an issue. It was  
32 recommended that the company should consider ad-  
33 dressing this.
- 34 – Quality: A large percentage of both Management  
35 and Staff stated that “product mistakes” were a pri-  
36 mary cause of plan revision. At the same time, rela-  
37 tively few respondents indicated that they use plans  
38 to manage quality, as indicated by its relatively low  
39 Importance Value in Figure 5. It was indicated in  
40 discussion that when a quality issue does arise it  
41 is often treated as a special case, with resources  
42 thrown at it until it is resolved. Drawing on the  
43 analysis of Section 4.6.2, it was recommended that  
44 the company consider incorporating quality more  
45 explicitly in the planning activity with a view to  
46 reducing these scenarios.
- 47 – Suppliers and cost: In the survey, respondents did  
48 not explicitly state that they use plans to manage  
49 supplier information. This was surprising because it  
50 was indicated that a large percentage of the Staff  
51 directly communicate with suppliers. Also, very few  
52 staff respondents expressed a strong interest in man-  
53 aging costs via the planning system; only two cases

were apparent in the survey results (see Mapping  
A in Figure 5). This could be cause for concern in  
an environment where much of the interaction with  
suppliers is managed directly by the staff. It was  
therefore recommended that the company consider  
how supplier interactions and cost could be better  
incorporated in the planning system, so these issues  
could be more explicitly monitored and managed.

The report was shared with the champion of our  
study in Company X. Due to geographic distance a  
visit and in-person discussion of the findings with the  
original interviewees was not possible, however upon re-  
viewing the report the project champion provided the  
following written comment:

“I think your summary is very valuable for us and  
we are already discussing if and how we should improve  
our system.”

#### 4.8 Discussion

The insights reported in Section 4.5–4.7 are derived  
from the interviews and survey undertaken in Company  
X. Thus, they are specific to that context. Nevertheless,  
some of the issues discussed are likely to also appear in  
other companies. For example, the lack of explicit in-  
tegration in plans between design-related content items  
and schedule-related information such as tasks and mile-  
stones is probably related to the focus of most planning  
tools and plan representations on the latter. There are  
relatively few established approaches that help to inte-  
grate product and design process information into a sin-  
gle representation, and those that exist remain mostly  
in the research domain (Eckert et al, 2017). It is also  
notable that the planning system in Company X was  
organised around a centralised Master Project Plan as  
a source from which individuals' weekly plans are de-  
rived. This provided a natural focus for the analysis of  
planning system coverage reported in Section 4.2. To  
apply this part of the analysis in a company that does  
not use a systematic, centralised planning system, it  
might be necessary to identify the set of most impor-  
tant plans to provide an equivalent focus.

The survey tool and analysis approach that were  
developed and demonstrated through the work with  
Company X could be applied to elicit, visualise and  
analyse the documented planning system in other com-  
panies, by following a similar process. An important  
feature of the approach was that analysis of the mod-  
els was guided and informed by an understanding of  
how the planning system operates in practice, which  
had been gained through the scoping interview and, in

1 this case, the discussions that took place with the re-  
 2 searcher while participants filled out the survey. This is  
 3 a critical point. Although MDM analysis of information  
 4 gained from the survey can identify important features,  
 5 such as strong clusters of implied dependency in the  
 6 documented planning system, the implication of those  
 7 features could be interpreted in several ways. Bringing  
 8 together insight from the survey and MDM analysis  
 9 with insight from the interview and discussions allowed  
 10 a deeper understanding to be synthesised than would  
 11 have been possible from any of these methods alone.

12 Although limited feedback on the approach was possible,  
 13 the comment from the study sponsor, shown in  
 14 Section 4.7, supports our conclusion that the approach  
 15 presented here offers a structured way of looking at a  
 16 company's planning activity that is grounded in data  
 17 and that can help to generate potentially useful insight.

## 22 5 Change propagation in the documented 23 planning system

24 The final analysis considered in this article views the  
 25 planning system from the perspective of plan change  
 26 propagation.

27 In this context, plan change propagation is defined  
 28 as the situation in which a change made in one plan  
 29 document requires knock-on change in other plan  
 30 documents, if the plans are to remain synchronised. Plan  
 31 change propagation occurs because of information that  
 32 is shared among plan documents, and because of de-  
 33 pendencies among that information. For example, in  
 34 Company X change propagates from the Master Project  
 35 Plan to individual task plans and vice-versa. In this case  
 36 the propagation is managed through a formal process,  
 37 as described in Section 4.2, but other propagation ef-  
 38 fects may not be recognised or explicitly managed.

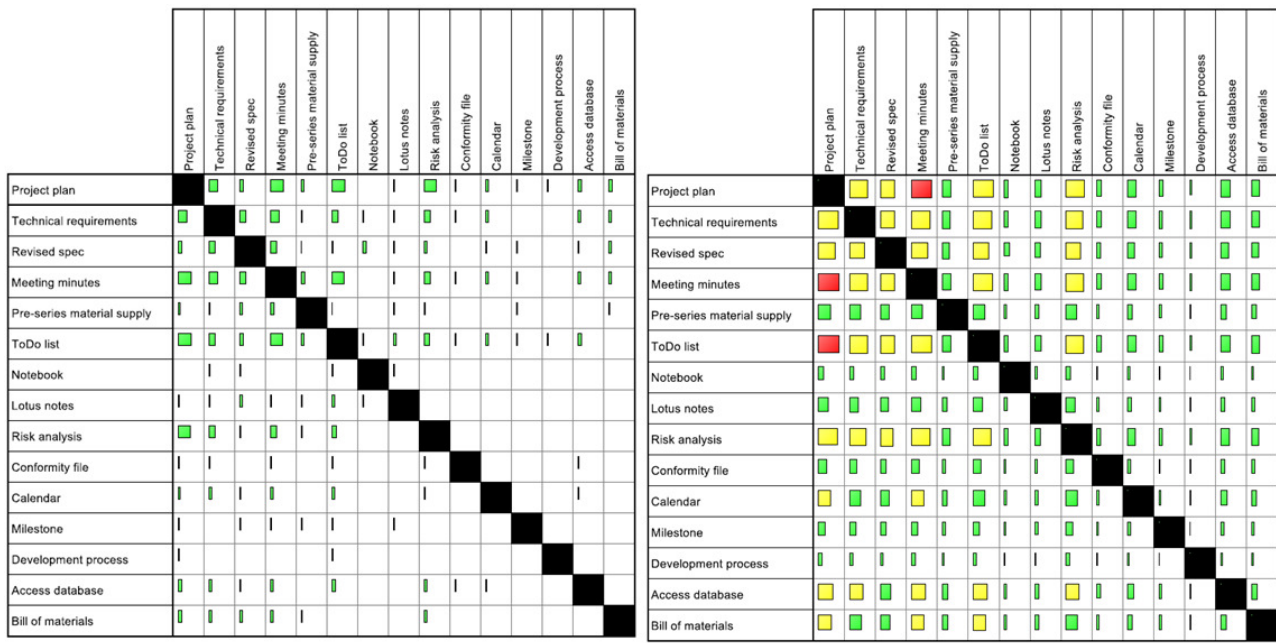
39 As with change propagation in other engineering  
 40 systems, the sensitivity of a plan to changes will depend  
 41 not only on its directly-connected neighbours, but also  
 42 on the overall organisation and interconnectedness of  
 43 the documented planning system. Understanding which  
 44 plans are influential in driving or receiving change may  
 45 be useful to focus attention on plans that are espe-  
 46 cially important to keep up-to-date. As noted earlier,  
 47 if a plan that is influential in the propagation network  
 48 is not kept up-to-date, important changes may not be  
 49 properly propagated and communicated to stakehold-  
 50 ers. This may have adverse impacts on coordination  
 51 and project performance. At the same time, it should  
 52 be noted that plan documents may not always need to  
 53 be updated after the plan is changed. For instance, the  
 54 different granularity and different specific information

in different plans might mean that one planning docu-  
 ment might not be updated, even if the same content  
 items change in another document. For these reasons a  
 probabilistic model of plan change propagation is ap-  
 propriate. Here it is assumed that the more strongly  
 a plan dependency is implied in the survey results, the  
 greater the probability of a particular change propagat-  
 ing between the corresponding pair of plan documents.

To demonstrate these ideas, the planning system  
 model shown in Figure 12 was used as the basis of a  
 change propagation analysis to identify documents that  
 are strongly influential in plan change activity in Com-  
 pany X. To do this, DSM A was extracted from Fig-  
 ure 12 and used to generate input data for the prob-  
 abilistic Change Prediction Method (CPM) developed  
 by Clarkson et al (2004). Numeric values in Figure 12  
 were normalised, so that the amount of shared content  
 between a pair of plans is interpreted as the probability  
 of change propagating between that plan pair. Then,  
 this was imported to the Cambridge Advanced Mod-  
 eller (CAM) (Wynn et al, 2010), yielding the visualisa-  
 tion shown in Figure 13 (left). CAM was used to com-  
 pute the CPM combined risk matrix, which is shown in  
 Figure 13 (right). The combined risk matrix indicates  
 the risk of change propagating from one plan to any  
 other, considering both direct and indirect propagation  
 routes. Modifying the normalisation factor mentioned  
 earlier impacts the saturation of the matrix, but the  
 relative risks associated with each implied dependency  
 remain similar.

Comparing the two matrices in Figure 13 illustrates  
 that the strongly-coupled plans towards the top-left of  
 the matrices are, as expected, most likely to propagate  
 change to one another. Of particular interest, some de-  
 pendencies that are relatively weakly implied or even  
 non-existent in the original matrix are revealed as im-  
 portant participants in plan changes once the possibility  
 of indirect routes is considered. This is, for example,  
 the case for the interaction between Bill of Materials and  
 To Do List.

To summarise, this section has demonstrated the  
 possibility of perceiving planning systems from a change  
 propagation perspective. There are many opportunities  
 for further work to study the implications of this per-  
 spective. For example, tracing the implied dependen-  
 cies in Figure 12 could be used to identify the indirect  
 propagation routes that cause unexpectedly strong im-  
 plied dependencies, providing guidance to ensure that  
 the necessary communication channels are in place such  
 that plans get appropriately updated in practice. A sim-  
 ilar propagation analysis might also be applied consid-  
 ering other domains of a Planning System MDM, for



**Fig. 13** Strength of implied dependencies between plans considering number of shared content items (left) and change propagation analysis results (right). The width of a block in the matrix indicates the combined risk of change propagating from a plan in the column to a plan in the row, considering the possibility of direct and indirect routes.

instance to identify process participants who are especially important in the planning system.

### 6 Limitations and suggestions for further work

There are several opportunities for further work to address limitations of the approach and to further explore how planning systems can be understood, modelled and improved.

Firstly, this article has focused on how the survey tool and MDM-based approach can be used to analyse an existing planning system. Project participants might also seek insights for designing a planning system for a project that has yet to be launched. This could be especially relevant to inform the development of complex products such as aircraft, where companies typically run a few very large-scale projects that involve significant unique elements. The approach could conceivably be extended to assist in this scenario. In particular, the survey tool PMAST could be used or adapted to assess the planning requirements of project stakeholders and ensure the development of a planning system that best meets the requirements of each stakeholder involved. Future work may investigate this possibility.

A potential limitation of the approach is the level of resolution that is feasible in the Planning System MDM. The main constraint is the need to keep the survey to a manageable size—the number of questions and thus time required to complete the survey are directly

related to the number of rows and columns shown in the Planning System MDM. As demonstrated in the case study, the level of resolution used here is appropriate to map the documented planning system and identify potential issues and problem areas for further, more detailed analysis. However, further work could investigate whether it is worthwhile to develop a planning system model with greater detail that incorporates deeper analysis of individual plan documents and perhaps their content. Another opportunity is to further study how properties of the planning system are related to the performance of design and development projects, for example in terms of effectiveness of coordination, the effort involved to keep plans up-to-date, and the ability of the project to stay synchronised in the face of unplanned changes and iterations. This might, for example, be approached empirically or through computer simulation of the micro-level dynamic interactions between decisions, processes and plans.

Finally, the insights gained from any modelling approach should justify the time and effort required to apply it. In the case study reported here the 14 survey sessions took between 1 and 3 hours each, plus a single scoping interview, for a total of approximately 30 hours invested by the company. This is comparable to a single 3-hour meeting with 10 participants. The modest level of effort seems justified considering the benefits obtained, both in terms of the detailed insights that are grounded in survey data and more generally from

increased awareness in the team of the planning system and its importance. Effort was also required from the researcher to attend the sessions and process the survey results. Concerning the latter, as a rough indication it should take no more than a few days' effort to repeat a similar analysis for a different company, assuming the calculations were done by creating spreadsheet formulae "from scratch" as done here. Although the calculations described in the text are not complex, the processing and formatting effort could be substantially reduced if the analysis was automated in a software tool populated directly by the survey. This is another possibility for future work, as is the application of automatic clustering algorithms and other graph-theoretic approaches to analyse planning systems.

## 7 Concluding remarks

Planning is an integral aspect of the design and development process which influences its coordination and, ultimately, its performance. Most analyses of design planning in the research literature focus on the sequencing and scheduling of projects, assuming that a single consistent activity network can and should be constructed. This article has taken a different perspective, building on the work of Eckert and Clarkson (2010) who consider planning to involve a multitude of planning documents that are used and updated throughout the course of a project. The article conceptualised the interaction between plans, plan content, and plan stakeholders as a planning system and argued that an appropriately-aligned planning system could help to avoid problems caused when key issues and dependencies are overlooked. The article has also demonstrated how a survey tool combined with MDM modelling and insight gained through interviews can be used to explore a company's planning system as viewed by that company's workforce, and shown how analysis of the models created with this approach can help identify opportunities to improve the planning system to better align it to the needs of its stakeholder community.

Overall, this article contributes a new perspective on understanding and analysing planning in design and development, focusing on the dependencies in a company's planning system. It also introduces a novel application domain for the DSM/MDM approach and for change propagation analysis. There is much work remaining to fully explore the possibilities.

**Acknowledgements** The authors gratefully acknowledge past and present collaborators for discussions on engineering design planning, especially Nicholas H.M. Caldwell and Claudia M. Eckert. We also thank the Editor, and the anonymous re-

viewers for sharing their insights. Special acknowledgement is due to all participants in the study at Company X, who wish to remain anonymous. Figure 1 is reproduced from Research in Engineering Design, Planning development processes for complex products, Vol. 21, 2010, p. 160, Claudia M. Eckert and P. John Clarkson, ©Springer-Verlag London Limited 2009. With permission of Springer.

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