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A Method for Modelling Business-Critical Architecture Decisions in Engineer-to-Order Companies

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Featured Application: The developed method is intended for engineer-to-order companies with a high product variety and who have decided to pursue modular product architectures as a means to address the negative effects of product variety.

Abstract: This article presents a method (the cross-functional architecture matrix, CAM) for identifying the most business-critical architecture decisions for companies applying product architectures to support the design and production of customised and highly engineered products. Although the product architecture literature describes the value of product architectures and suggests concepts and methods for modelling product architectures, existing methods tend to focus on a select few parts of the value chain or a few functional disciplines despite engineer-to-order (ETO) companies being highly cross-functional. Furthermore, the literature suggests that the practical implementation of product architectures is hindered by the complexity of the architecture models and the large number of decisions involved in the implementation and maintenance of the architecture. In this article, we test the suggested method in a case of a company that designs manufacturing plants (usually an investment in excess of 200 M€) and where three major equipment systems were chosen. For each system, cross-functional architecture matrices were applied. In each case, we found that only five architecture decisions had to be made to achieve significant improvements in the system's performance, including a 30% reduction in installation hours, 76% of commissioning activities moved from the site to workshop, a 6% faster time to production, and a 12% total cost reduction. Practitioners in ETO companies can use the CAM method to support their product architecture development, while researchers can utilise it for future studies on the implementation of product architectures across functional domains and value chains.

Keywords: engineer-to-order; modularisation; product architectures; systems engineering; product platforms; value chain; cross-value-chain; cross-functional

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1. Introduction

Engineer-to-order (ETO) companies are characterised by offering complex products (often including more than 100,000 components) that are engineered and produced only after receiving customer orders, which necessitates engineering activities during the quotation and delivery processes. ETO companies play a crucial role in various industries, including manufacturing, construction, and custom machinery, where tailored solutions are paramount. These industries are now seeing even more product variety with the need for new technologies and solutions as part of the green transition. Nevertheless, the product variety that stems from the ETO characteristics has been shown to have a significant lead time [1,2] and cost drivers [3,4] associated with it. Several studies have proposed various methods to help companies address the impact of product variety on engineering [5,6], manufacturing economies of scale [7,8], and many other cross-functional disciplines [9] and value-chain activities [10]. Despite these efforts, two main challenges seem to hinder the practical implementation of product architectures when applying the current methodologies.

First, the literature suggests that ETO companies are hindered due to the complexity of the architecture models and the large number of decisions that must be made throughout the implementation and maintenance of the architecture. Løkkegaard et al. [11] argue that, while the existing models tend to produce thousands of architecture decisions that, in principle, all bring value, relatively few are truly business-critical. With countless architecture decisions to govern, it is difficult for company management to know where to focus their governance efforts. As a result, their efforts are easily lost in non-critical details, and they fail to provide the level of governance needed to successfully reap the benefits of product architectures [12].

Second, although the literature recommends prioritising only critical architecture decisions, the characteristics of ETO companies require an architecture that encompasses decisions in all cross-functional disciplines and across the full value chain. Foehr et al. [13] argue that existing methods tend to focus on a select few parts of the value chain or a few functional disciplines; however, the parts of the value chain in focus (typically manufacturing or mechanical engineering) are not always the sole or most critical drivers of the cost and lead time. For example, companies with low product volumes do not see traditional benefits due to economies of scale.

In essence, few papers have described a methodology for identifying and prioritising only the business-critical architecture decisions of a product portfolio. Furthermore, the papers that discuss business-critical decisions tend to focus on only one or two parts of the value chain and do not provide guidance on how to structure the analysis cross-functionally and across the full value chain.

To address this gap in the literature, we developed a holistic method (the cross-functional architecture matrix, CAM) to support ETO companies in developing modular architectures. The method is tested on three product systems (i.e., cases) in an ETO company in the processing plant industry. Section 2 covers the theoretical background, reviewing the existing literature on product architectures and their impact on business-critical activities in ETO companies. Section 3 describes the materials and methods, detailing the case study approach and data collection techniques such as interviews and workshops used to evaluate the cross-functional architecture matrix (CAM) method. Section 4 presents the results from the case study, demonstrating how the CAM method helps identify and prioritise critical architecture decisions to improve system performance, reduce costs, and shorten lead times. Finally, Section 5 discusses the implications of the study's findings for both research and practice, highlighting the contributions of the CAM method in addressing the gaps in the existing literature and providing recommendations for future research and practical applications in ETO companies.

2. Theoretical Background

This section discusses the literature on the dependencies between the design variety and the variety in different business-critical activities cross-functionally and across the value chain.

2.1. Integration Cross-Functionally and Across the Value Chain

The importance of understanding dependencies across different functional disciplines and across the value chain is highlighted by Foehr et al. [13]. They describe in this paper how the poor integration of product variety with a multitude of cross-value-chain and cross-functional activities can have significant impacts on the costs, lead times, or other business-critical parameters:

(a) The poor integration between product variety and downstream product lifecycle phases, such as maintenance activities, can negatively impact product performance (e.g., customers of wind turbine manufacturers are willing to pay a higher one-time manufacturing price if their maintenance costs can be reduced over a 30-year lifespan);
(b) Product variety can lead to a poor integration between mechanical engineering and other disciplines (e.g., offshore structures, such as oil rigs, have a significant integration dependency between mechanical and civil engineering);
(c) Design variety drives fewer resources in manufacturing in companies with low product volumes, such as ETO companies. Due to these low volumes, they do not see the traditional benefits of economies of scale.

Better integration for such cross-functional dependencies has been studied in several areas. For instance, the framework proposed by Mueller et al. [14] offers a practical approach to structuring an analysis of how product design impacts the commissioning activities of ETO companies. The focus of aligning the product principles with commissioning performance is highlighted in this paper as a useful means for improving the integration between the two different functional areas of product design and commissioning. Borgue et al. [15] supported the related findings through a case study on the test and qualification activities in the architectural design of satellite propulsion systems. Additional methods for cross-functional integration are explored in Section 2.3. Nevertheless, the two aforementioned papers did not explicitly explore the potential of prioritising such architecture decisions on commissioning according to business criticality.

2.2. Prioritisation of Business-Critical Architecture Decisions

The work of Sanchez [12] highlights that a critical element in successfully applying product architectures is employing a certain level of governance on the details that are critical for the strategic objectives of the business. As underlined by Løkkegaard et al. [11], care is needed when prioritising architecture initiatives to ensure that company management targets architecture decisions that are truly business-critical for the company. Thus, Løkkegaard et al. suggest that companies establish a frame of reference in their governance for new-product introduction based on several ‘game rules’, or ’business-critical design rules’ (BCDRs), that outline the most business-critical features of the product and production architecture. In their case study of a global OEM, such BCDRs provided a potential 35% reduction in investment in manufacturing equipment along with a reduced time-to-market [11].

The insights described above are further supported by Skinner [16] in their theory on production systems and their requirements. It is argued that companies designing new production systems often find themselves unable to prioritise requirements due to the ambition of wanting to consider every single requirement from the start. As such, the inability to distinguish between significant and insignificant requirements shows that companies mistakenly focus on the wrong requirements when the requirements inevitably change during development. Therefore, Skinner suggests that companies prioritise production system requirements based on the overall company strategy on cost, quality, flexibility, delivery, and innovation [16]. While this is the case for mass production systems, contingency theory [17] elaborates on the prioritisation for the strategic objectives of companies in that evaluating exactly what is business-critical is dependent on the internal and external factors for the company. Therefore, it is critical that we understand which cross-functional and -value chains are truly critical for the company at hand.

2.3. Methods of Mapping and Improving Product Architectures

To address problems related to product variety, researchers have produced a number of methods for mapping and improving product architectures [18]. An early example is the design structure matrix [19]. It was later used in a variety of contexts to generate binary overviews that indicate where design variety in one system affects the designs of other systems or value-chain activities (e.g., [19,20]). As such, it has the potential to show dependencies across many different activities. Having said that, the method does not indicate the severity of a given dependency or the extent to which the dependency is critical for the cost and lead times of other activities in the value chain.

Harlou [7] suggested using a graphical modelling technique called the Product Family Master Plan (PMFP), which can support the visualisation of how product variety impacts resources spent on mechanical engineering and product manufacturing. The graphical nature of the modelling technique means that the design of the analysed dependencies is clearly illustrated. This results in a more solution-oriented approach, as the design of dependencies can serve as a basis for further investigation into the design of product interfaces for separate modules. The modelling technique also employs a high level of abstraction, and, as such, it could be used to model other cross-functional engineering activities in the value chain. A recent example of this is the MESA tool proposed by Askhøj et al. [21], which extends the PMFP by including electrical and software engineering dimensions. Küchenhof et al. [22] also shared their findings on a comparable topic by introducing a modified V-model. However, neither of the tools explicitly addresses non-design engineering activities, such as procurement or commissioning activities.

Similar to the previous modelling technique, Bruun et al. [23] developed a modelling technique to help manage the impact of product variety: the Interface Diagram. It shares many of the benefits of the PMFP, such as enabling product teams to better make architecture design decisions that limit the effects of product variety. While these are valuable attributes, the modelling technique does not explicitly indicate the impact of product variety and, thus, business criticality. It does not evaluate which product variance critically affects the cost and lead time of other activities in the value chain. While Løkkegaard et al. [11] provide relevant guidance on prioritising according to business criticality, their paper only looks across the product and production domains.

From a more quantitative perspective, de Weck [24] developed a mathematical approach to modelling architecture decisions that focuses on determining the optimal number of platforms within an architecture. Similarly, Siiskonen et al. [25] investigated how choosing the optimal number of modular variants impacts production costs. In addition, Siiskonen et al. [26] employed a computational model to measure the cost implications on manufacturing. However, due to the model's focus on single pre-defined architectures, the design decisions modelled are inherently limited in flexibility to the extent that is demanded in ETO companies.

Vollmar and Gepp [27] proposed a comprehensive framework for modular product development based on knowledge obtained from six ETO companies. The technology domain of the framework focuses on the need for system integration across all parts of the value chain, which is particularly critical for ETO companies. Unlike the previously mentioned models, this framework gives ETO companies a broader overview of the changes needed for all parts of the company. This includes changes to the business, technology, processes, and people to achieve a successful system integration and decouple the design variety. While the framework covers many crucial elements, it offers limited practical advice on how to explicitly structure an analysis that identifies which systems are in need of such critical integrations into other parts of the value chain.

Methods similar to the one described by Mueller et al. [14] exist that describe other parts of the value chain, one at a time. For example, Brosch et al. [28] described how to design modular architectures for supply chain requirements; Halfmann et al. [29] described how to design modular architectures for assembly; and Elstner and Krause [30] described how to design modular architectures for ramp-up. While the insights gathered from the studies all prove useful as inputs to modular architectures, their limitations are similar to those of the method proposed by Mueller et al. [14].

Similarly, Blees [31] proposed the Module Process Chart (MPC) as a tool for allocating module drivers and module driver specifications to modules across all parts of the value chain. The chart can be used to identify potential architecture dependencies that span multiple activities in the value chain. However, the method is binary in its visual representation of dependencies on other parts of the value chain. It does not offer any formal visualisation practices that illustrate how (and how severely) the design of the dependencies impacts critical parts of the value chain.

Furthermore, Krause et al. [10] proposed a framework (PKT) that prescribes the need to combine Blees's [31] MPC with an analysis of product variety in individual parts of the value chain, such as design for supply chain requirements [28], modularisation for assembly [29], and design for ramp-up [30]. The framework prescribes the use of these models to check the compatibility of already proposed modules with all aspects of the value chain and to identify conflicts. They also prescribed the use of Module Interface Graphs [32] to aid in this process. More data-driven approaches to module requirement validation have been investigated by Wagenmann et al. [33] to increase the usefulness of this modular approach. The toolkit in the PKT framework allows case-specific combinations and adaptions of the evaluated methods and tools to align modular architectures across critical parts of the value chain. However, a practical approach to adapting the toolkit for analysis is not elaborated on in the papers.

Similar frameworks, such as the Architecture Mapping and Evaluation framework [34] and the "13 steps for developing a platform concept" [9], offer a thorough overview and prioritisation of the most critical steps needed to assess modular product architectures. However, similar to the PKT framework, there is no elaboration on a practical approach to conducting the required analysis of the impact of product variety across critical parts of the value chain.

Other aspects of cross-functionality and product architectures have been explored by Breimann et al. and Otto et al. [35], who investigated how electromagnetic and thermal fields influence product architectures on a component and functional level, respectively. In a broader context, Zuefle et al. [36] explored the prospects of cross-functional collaboration in modular design. Several benefits to companies were featured by Zuefle et al. [37], such as module upgradeability and plug-and-play replacement, all of which are useful attributes for companies. However, none of these studies discusses how to structure an analysis for prioritising such cross-functional architectures according to business criticality.

Additional lifecycle perspectives in product architectures were investigated by Küchenhof and Krause [38] and Küchenhof et al. [39] concerning the use of architectures across product generations through assessments of the activeness and centrality of product components and modules. However, strictly speaking, the papers do not explore how to model architecture considerations across any functional discipline.

Pakkanen et al. [6] proposed a method (the Brownfield Process) for managing the key engineering concepts, which they suggest should be the centre of modular product development. The method provides great insight into the importance of considering architecture decisions in relation to the other key engineering concepts of partitioning knowledge, set of modules, interfaces, and configuration knowledge. However, while the method only exemplifies a modelling principle for showing product variety's impact on other mechanical designs, it does not explicitly elaborate on how to determine how variety in key architecture decisions impacts the cost and lead time across multiple aspects of the value chain.

2.4. Lean and Digital Supply Chains in ETO Companies

From the perspective of lean principles for efficiency, several tools and methodologies have been proposed to improve the efficiency in ETO companies. One example is Braglia et al. [40], who present the Project Cost Deployment method for identifying and quantifying waste. Similarly, Bertolini et al. [41] present the Project Time Deployment method for lead time reductions. The methodologies show significant potential for improving the cost and lead time in ETO companies. While the papers in their original forms do not directly address architecture decisions, the emphasis on process optimisation and waste elimination strongly supports the importance of aligning architecture choices.

Finally, from the perspective of the digitalisation of supply chains and the rapid developments in this area across various sectors [42], significant improvement opportunities for ETO companies have been reported. According to Taghiour et al. [43], ETO companies stand to benefit from the enhanced agility and data-driven decision-making enabled by digital technologies. The integration of the Internet of Things (IoT) or Artificial Intelligence (AI) is revolutionising various aspects of supply chain management [44]. For instance, Schulze and Dallasega [45] present a novel framework that classifies traditional losses in ETO manufacturing environments and maps them to suitable Lean and Industry 4.0 methods to enhance productivity and efficiency in ETO companies. However, the framework in its original form does not explicitly address the variance in product architecture decisions for ETO companies. Finally, Woschank and Dallasega [46] introduce a prescriptive maintenance system with predictive analytics and intelligent control to address maintenance needs. While highly relevant, the paper does not address how this could be used for harmonising architecture decisions across the full value chain since it mainly discusses maintenance activities.

2.5. Litterature Summary

In conclusion, it is clear that the abovementioned literature all contribute in part to valuable methodology and modelling for the identification of architecture decisions. Although product architecture is a highly cross-functional topic, many scholars only explicitly address one or a few parts of the value chain in their modelling. Few scholars address all cross-functional and cross-value-chain elements, and those who do tend to forgo evaluating or indicating the criticality of the architecture decisions to the business of the company. The literature revealed that the focuses of the existing methods can be divided into three categories: (1) cross-functional dependency modelling, (2) cross-value-chain dependency modelling, and (3) business criticality modelling (Table 1).

The lack of a prioritised and more holistic perspective on all cross-functional and cross-value-chain elements makes it difficult for ETO companies to provide the necessary governance of architecture decisions needed for successful implementation. Therefore, we identified a gap in the methods and tools used to support product developers in addressing business-critical cross-functional and cross-value-chain architecture decisions for ETO companies.

Table 1. Overview of how the reviewed literature addresses cross-functional architecture matrix (CAM) method concerns. The light green and dark green colors are there to highlight which articles partially and fully address the criteria.

		Cross-Functional Architecture Matrix (CAM)		
		1. Addressing Full Cross-Value-Chain Design Dependencies	**2. Addressing Full Cross-Functional Design Dependencies**	**3. Addressing Prioritised View of Only Business-Critical Design Dependencies**
State-of-the-Art	Design Structure Matrix—DSM [19]		▨	
	DSM-based modularisation approach [47]	▨	▨	
	Product Family Master Plan—PMFP [7]		▨	
	MESA tool [21]		■	
	Interface diagram [23]		▨	
	Mathematical modelling [24]	▨	▨	
	Standardisation framework [27]	■	■	
	Commissioning framework [14]	▨		
	Design for supply chain requirements [28]	▨		
	Modularisation for assembly [29]	▨		
	Design for ramp-up [30]	▨		
	Module Process Chart—MPC [31]	■		
	The integrated PKT framework [10]	■	■	
	Module Interface Graph—MIG [32]		▨	
	Architecture Mapping and Evaluation framework—AME [34]	▨		
	13 steps for developing a platform concept [9]	■	■	
	The Brownfield process [6]		▨	
	Modified V-Model for supporting the new development of cyber-physical product families [22]		▨	
	Pharmaceutical product modularisation as a mass customisation strategy to increase patient benefit cost-efficiently [25]	▨	▨	
	Modelling the cost–benefit impact of integrated product modularisation and postponement in the supply chain for pharmaceutical mass customisation [26]	▨	▨	
	Design for test and qualification through activity-based modelling in product architecture design [15]	▨		
	Data-driven modelling of the functional level in model-based systems engineering—optimisation of module scopes in modular development [33]		▨	
	A method for optimising product architectures for the management of disturbance factors [48]		▨	
	Incorporating field effects into functional product-system architecting methods [49]		▨	
	Coping asynchronous modular product design by modelling systems-in-system [37]		■	
	Initial integral product and assembly structuring [38]	▨		
	Assessing the influence of generational variety on product family structures [39]	▨		
	Business-Critical Design Rules—BCDRs [11]		▨	■
	Lean and Industry 4.0 mitigating common losses in engineer-to-order theory and practice: an exploratory study [45]	▨	▨	
	The impact of Logistics 4.0 on performance in manufacturing companies: a pilot study [46]		▨	

3. Materials and Methods

The evaluation of the CAM method was carried out in collaboration with an ETO company. A case study method was used to facilitate the investigation because it can help capture and formalise industry practitioners' knowledge and experiences and provides a platform for developing theories from practical insights and moving on to the testing stage [50]. All of these attributes are relevant for shaping the CAM method proposed in this study. The decision to conduct the case study with a single case company enabled a deep study of the research problem [51]. The data collection techniques used in this study were semi-structured expert interviews and participatory observations in meetings and workshops. Technical documents were also examined to provide context for populating the matrix.

3.1. Case Context

The company chosen for this study delivers state-of-the-art manufacturing plants to a global market. The company is concerned with all major parts of the delivery process, namely, selling, designing, engineering, procuring, installing, commissioning, and running the facilities. The delivery covers not only the manufacturing equipment itself but also the buildings and infrastructure needed to operate them. Each plant is customised to a set of unique project-specific requirements, and the delivery process is carried out in parallel with other projects. Each project is run by a distinct project team.

Three major equipment systems were selected for analysis by the company. Each equipment system covers one or more critical steps in the overall manufacturing process and is developed by a separate team. The systems also comprise technical elements that have a high dependency on project-specific requirements and, as such, have seen a great deal of design variance historically. For each equipment system, the designs from the three latest projects were analysed. The three most recent projects were chosen with input from the company management team. These projects and systems were chosen because there was anecdotal evidence of them having high design variance.

Since the case company had been working with modular architectures since 2012, the company shared the main concerns of the study: how to address product variety across critical parts of the value chain. This alignment of interests is why this company was chosen for the study.

Due to confidentiality, it was not possible to show the full content of the analysis for all the systems. Only an excerpt of the analysis of System 1 (Fluids) is shown.

3.2. Data Collection and Analysis

The case study, which is presented in Section 4, was carried out in two phases. The first phase set out to understand the efficacy of the method in an industry context. To do this, activities were organised to populate the first and second parts of the model, which was carried out by the company (as described in Section 4.2). Interviews were conducted with senior engineers and technical project managers to populate the first part of the model (see Table 2). The interviews were conducted over a four-month period. Throughout the project, updates were presented to the management team members on a biweekly basis so that they could provide feedback on both the practical execution and the overall strategy to reach the desired goal.

Table 2. Data collection through semi-structured interviews, meetings, and workshops.

Job Position	Experience at the Case Company	Method	Purpose	Number	Total Duration
Equipment Engineer 1	9 years	Interview	Understanding of equipment area and populating primary technical system in CAM model of case 1, 2, and 3, respectively. In part, these interviews helped populate the first part of the CAM matrix.	6	6 h
Equipment Engineer 2	14 years	Interview		5	5 h
Equipment Engineer 3	18 years	Interview		5	5 h
Technical Project Manager 1	20 years	Interview	Understanding of the primary technical systems impacts on sorrounding systems in project 1, 2, and 3 respectively. In part, these interviews helped populate the first part of the CAM matrix.	4	4 h
Technical Project Manager 2	14 years	Interview		7	8 h
Technical Project Manager 3	12 years	Interview		5	5 h
Civil, Equipment, and Technical Project Managers	4–20 years	Workshop	Presentation and discussion of primary technical system impact on on secondary systems. In part, this workshop helped populate the second part of the CAM matrix.	1	3 h
Procurement Team	4–12 years	Interview	Understanding of the companies collaboration agreements with suppliers and impact on commisioning steps. In part, this workshop helped populate the second part of the CAM matrix.	3	3 h
Civil Engineer	6 years	Interview	Understaning of civil impact on loads, and strucutral steel and pipe routing. In part, this workshop helped populate the second part of the CAM matrix.	3	3 h
Electrical Engineer	7 years	Interview	Understanding of electircal engineering impact on commisioning. In part, this workshop helped populate the second part of the CAM matrix.	2	2 h
Process Engineer	26 years	Interview	System changes and documentation impact on running in steps. In part, this workshop helped populate the second part of the CAM matrix.	2	2 h
Civil, Equipment, Procurement, Electrical, and Technical Project Managers	4–20 years	Workshop	The workshops were focused on establishing consensus on the holistic overview of the primary technical system and secondary engineering, and validate the critical dependencies found.	3	9 h
Management Team	2–25 years	Meeting	Status meetings to guide both the practical and strategic approach of the study.	20	20 h
Technical Project Manager, and Management Team	4–20 years	Workshop	The workshops were dedicated to reviewing findings from the CAM method to explore ideas for decoupling or clarifying the dependencies. Procedures for handover of suggested initatives for further technical due diligence and implementation was also discussed.	3	9 h

In addition to the interviews, workshops were organised to populate and discuss the second part of the model. The workshops were conducted over a two-month period, slightly overlapping with the period for the interviews. The participants in the first two workshops gave input from a range of different competence areas and business units. While the researchers helped facilitate the work with the CAM method, they did not actively participate in identifying the architecture dependencies.

The second phase investigated the potential impact of the identified initiatives. This investigation was first based on objective estimates of cost and lead time reduction potentials initiated through semi-structured expert interviews with senior engineers. Second, it reviewed how the results of the CAM method initiated strategy changes for senior engineering management. This was carried out through observations during reflection meetings with the management team.

3.3. Use of Generative AI

Finally, generative AI was used in the editing of the manuscript for overall grammar, sentence structure, and clarity.

4. Results

4.1. Introducing the Cross-Functional Architecture Matrix

This section develops a method named the cross-functional architecture matrix (CAM), which supports ETO companies in the structured mapping and analysis of the variance in past projects and its cross-functional and cross-value-chain impacts on the cost and lead time. The proposed method extends the existing research by using it as a basis for developing a methodology that addresses the previously mentioned gaps. Specifically, it focuses on how to model the design variety of technical systems and the relation between the design of technical systems and dependencies to other business-critical activities cross-functionally and across the value chain. The CAM method can help ETO companies identify business-critical architecture decisions that decouple the variance from key parts of the value chain. The following subsections describe the three main steps of the CAM method:

1. Modelling cross-functional architecture;
2. Analysing cross-functional architecture;
3. Decision-making on cross-functional architecture.

4.1.1. Modelling Cross-Functional Architecture

Figure 1 illustrates how the data are modelled using the CAM method. Subsequently, its parts are described according to the letters seen in the figure.

(A) The matrix splits the model into two main parts: (1) the primary technical systems and (2) secondary engineering. The primary technical systems include systems that directly serve a product function or requirement, while ‘secondary engineering’ concerns the mapping of secondary technical systems and engineering processes that serve the primary technical systems, i.e., processes through the full value chain and across functional disciplines. Splitting the model in this way enables the identification of dependencies between the two parts. As noted by Sanchez [52], it is only when these dependencies are addressed that one can harvest the benefits of product architectures.

(B) Along the horizontal axis, the mapping highlights the primary systems and sub-systems that make up the product. The sub-systems highlight the functions comprising the primary system. The segmentation of systems should be such that different functions, technological areas, or organisational sections are separated where possible. The main systems are divided into smaller sub-systems to handle the high complexity, as pointed out in the Theory of Technical Systems [53]. It allows for comparisons of the sub-systems across different projects for both halves of the matrix. In addition to sub-systems, the system layout should be represented to show the relative positioning of the systems, indicating the various interfaces and interactions between those, thus revealing critical cross-functional dependencies across primary sub-systems, which is a key part of defining an architecture [6]. The first system to map should be determined in collaboration with company stakeholders, as they possess key knowledge of which systems have a high impact on the cost and lead time.

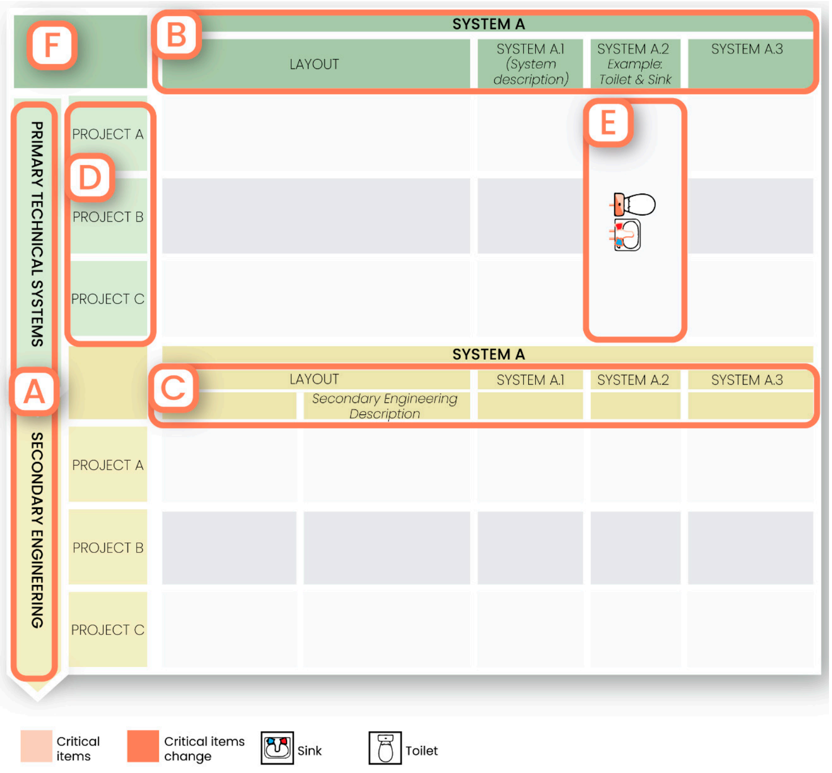

Figure 1. Generic overview of the CAM method. The letters on the figure corresponds to an explanation in the text marked with the same letter.

(C) In the bottom half, both the sub-systems and processes of secondary engineering should be highlighted. This is explained in more detail in step (F).

(D) In this column, recent projects from the company's past portfolio are mapped along the vertical axis. The projects should be identical in both halves of the matrix. Mortensen et al. [34] argued that, by analysing past projects, good and bad solutions can be distinguished from each other, ensuring that the good solutions are carried over to the new architecture. When choosing which projects to analyse, it is important that they share some similarities for the matrix to work. As many different sizes and types of projects exist in the ETO business, it can be difficult to create one set of rules to follow when choosing projects to include. Therefore, project selection should be considered individually for each case. In Section 4.2, we present a case study of several projects that exemplifies the selection process.

(E) The appropriate mapping of individual cells is critical in allowing for the successful analysis of the variation between projects. The mapping shall visualise the individual principles or designs that are employed to achieve the given sub-system, process, or layout in the respective projects. The visualisations representing the designs or principles shall have an abstraction level that highlights the design features whose variance impacts across competence areas or secondary engineering. In practice, this abstraction level is determined iteratively with stakeholders. This illustrative modelling is key to establishing a common ground from which stakeholders across the value chain and functional areas can understand and discuss the different technical systems and engineering processes [23]. The case study presented in Section 4.2 will provide an example of a sufficient abstraction level.

(F) This step describes the general principles for prioritising which processes and systems should be mapped. The fundamental principle is that not every single system or process should be mapped. The mapping should first be started with the primary technical systems. This principle is analogous to the one suggested by Skinner [16] on the design of production systems and their requirements. Skinner argues that, in cases where every single requirement is considered at the start, the development of the production system does not succeed as intended due to the company's inability to distinguish between significant and insignificant requirements, thereby mistakenly focusing on the wrong requirements when they inevitably change during development. Furthermore, the product architecture literature argues that, if too many architecture elements are mapped, it can be difficult for the company's management to know where to focus their governance efforts, which can result in too much focus on details that are not critical to the company's performance [11,12]. As the primary technical systems are mapped, stakeholders should evaluate which secondary engineering and its variance have a major impact on business-critical parameters and, therefore, should be mapped. As supported by Hubbard et al.'s framework [54] of value-chain logic, not every part of secondary engineering can be truly critical for every system or sub-system. Therefore, time should not be spent unnecessarily mapping secondary engineering that is not business-critical. For instance, for some systems, it is the variance in commissioning principles that is critical, while, for other systems, it is the variance in the principles of structural support. Additionally, some sub-systems can have an impact on multiple parts of the value chain, while others have no significant impact. More importantly, the use of company stakeholders for this step, step (F), is supported by contingency theory [17], in that evaluating exactly what is business-critical is dependent on the internal and external factors for the company. Therefore, stakeholders should evaluate the design variance based on a gross list of potentially business-critical criteria. This could include the project cost, lead time, project risk, opportunity cost, environmental impact, or quality. With these criteria, stakeholders should establish a threshold to determine when a certain variance is considered to have a great enough impact to be business-critical. The estimate for whether the threshold is met does not need to be perfectly accurate but should merely determine whether the impact in a worst-case calculation is still over the threshold. This selection process is key to ensuring that the methodology works, and this is further explored in the following section.

4.1.2. Analysing Cross-Functional Architecture

When deciding which systems require business-critical architecture decisions, two criteria must be met. First, either cross-functional [6] or cross-value-chain [13] variance needs to be present in the analysed system. Second, there must be the potential to mitigate the variance either by (a) decoupling the dependency between the two varying elements [55] or (b) clarifying their dependency through an interface description [23]. If these two criteria are met, a critical architecture decision is needed to address the variance in the respective elements. Thus, two main types of variance are sought when analysing architecture: cross-functional and cross-value-chain variance. The analysis of the CAM is exemplified in the following section through a hypothetical case of a bathroom design company. It should be noted that the example of custom bathroom deliveries has been selected for pedagogical reasons only—that is, to illustrate the CAM method without confusing the reader with too many technical details. Subsequently, in the case results, the method is applied to an ETO company delivering production facilities.

The example company is concerned with the specification and detailed design of bathrooms for multi-family housing. The company delivers one design for all bathrooms in an apartment complex, but the bathroom design will change from apartment complex to apartment complex. The scope of the bathroom design includes all building fixtures, such as showers, sinks, and white goods, as well as tiles, cabinets, plants, and so on. The company does not do in-house design and construction of the structure/building where the bathrooms are situated. They do not install plumbing or electrical systems. All of this is handled by suppliers or contractors further down the value chain. Design changes that impact activities on the construction site are seen by the bathroom company as the most business-critical elements. The company has several anecdotes of budget overruns due to changes in this phase and emphasises that this is the most time-consuming part of the project. The company wishes to better understand why their bathroom projects always end up so expensive and late, which is why they employ the CAM method.

As depicted in Figure 2, three of the latest delivered bathroom projects were chosen for the analysis. The business-critical systems mapped in this example consist of a bath fixture, a toilet and sink combo, and a textile care solution. The company offers two bath fixtures: either a bathtub or a shower cabin. The designers require the toilet and sink to be placed next to each other as pairs. Although the company offers only one type of toilet, the sink comes in a square and a rounded variant. This is not included in the mapping, as the variance does not impact the on-site construction phase. Similarly, the floor tiles come in different colours, and cabinets of different sizes are mounted on the wall, but neither has an impact on the business-critical systems or secondary engineering. Lastly, textile care is included, as the company has recently decided to offer a combined washer/dryer unit, which they have not offered in previous projects.

Step 1 in this part of the method (see Figure 2) analyses the three bathroom designs to exemplify how cross-functional variance is identified.

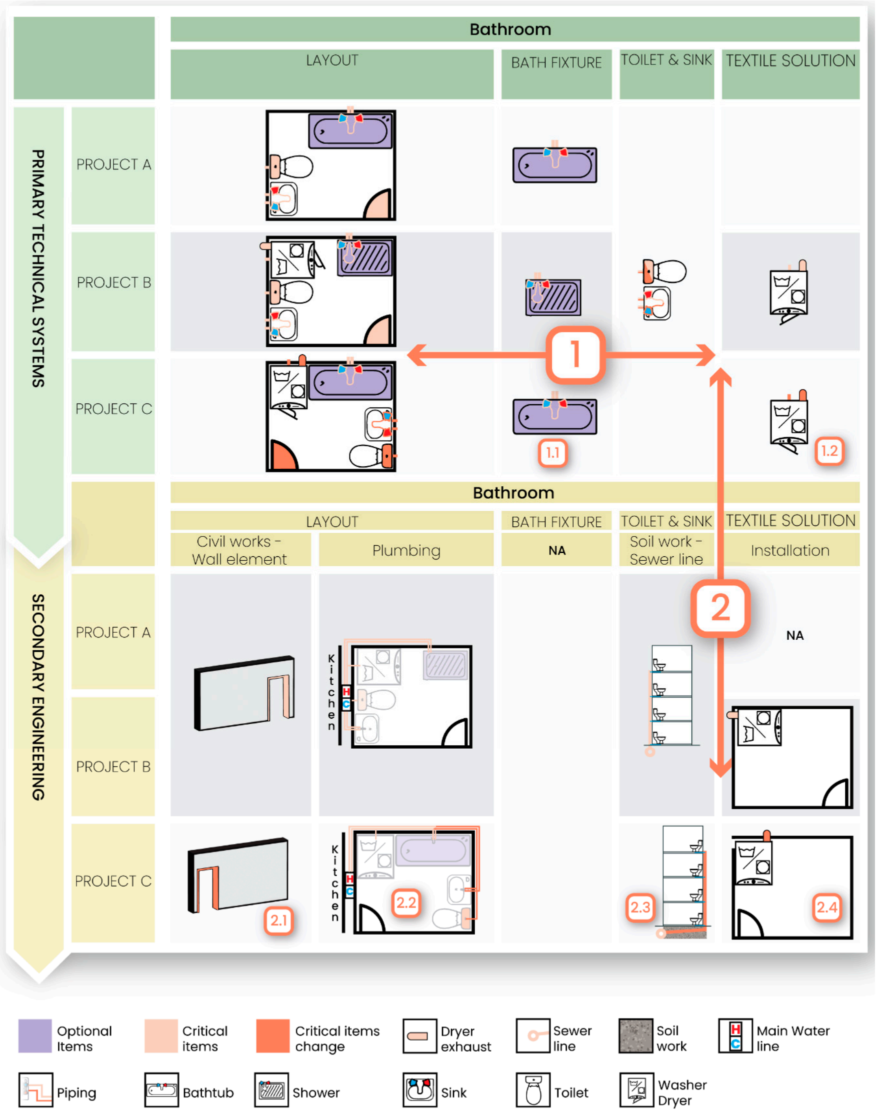

Figure 2. Generic populated cross-functional architecture matrix (CAM). The numbers on the figure corresponds to an explanation in the text marked with the same number.

In Project A, a bathtub is included in the design, whereas, in Project B, the bath fixture has a smaller footprint because the project demands a shower cabin instead of a bathtub. The smaller footprint prompts the salesperson to offer the washer/dryer unit to the customer, who agrees to include it. The washer/dryer unit is placed in the empty space left by the shower. However, in Project C, a problem arises: the design of Project C requires both the washer/dryer unit and the bathtub. Since there is no space for both of them in their original position, the washer/dryer orientation is changed to accommodate the new position of the other systems.

In Project C, the change in the washer/dryer orientation means that the door to the drum can no longer open properly if it is right-hinged (it would become too cramped between the door and the wall). Therefore, a design change to the washer/dryer is needed to mount the hinge to the door on the other side.

Step 2 in Figure 2 concerns the variance between primary engineering and secondary engineering (variance across sheets). This is identified by looking at one sub-system at a time and identifying how changes to the primary technical systems impact the different parts of the value chain in secondary engineering. The following examples in Figure 3 show the identification process of cross-value-chain variance:

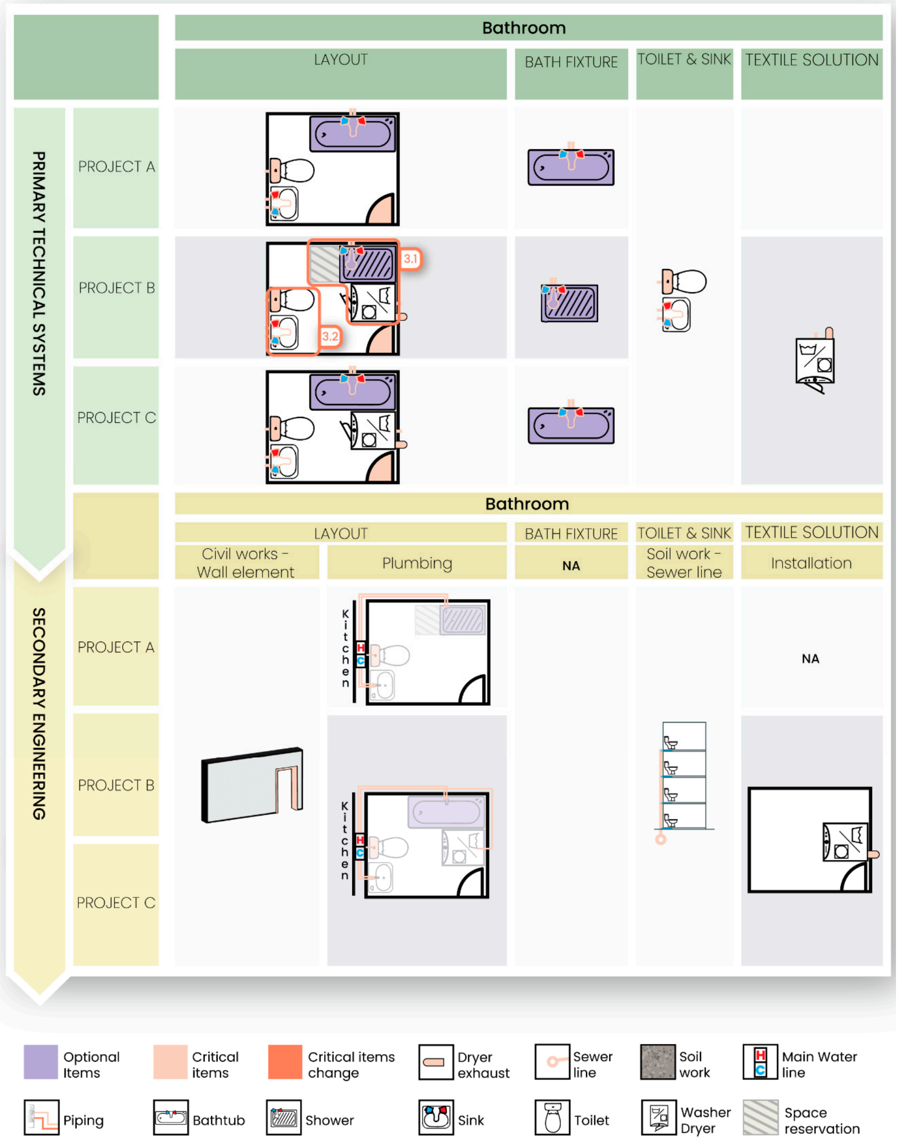

Figure 3. To-be scenario illustrated using the cross-functional architecture matrix (CAM).

The designers have to move the toilet/sink combo to make space for the washer/dryer and bathtub. Moving the toilet/sink means that the door has to be moved. When consulting the civil engineer about the bathroom, they report that the most resource-intensive task in their delivery is the engineering and construction of structural elements. Thus, while moving the items inside the bathroom does not impact the structural design, the door location does. Since the door is placed in a structural wall, in Project C, it has to be completely re-engineered with reviews of both statics and the constructability of the new wall element.

Moving the toilet and sink to the other side of the room in Project C negatively impacts the plumber. Their work becomes more expensive because the new location is further away from the main water lines. The main water lines cannot be moved because they have to be located close to the kitchen. Thus, the plumber has a longer installation time and higher material costs due to the need for longer pipes.

The toilet placement in Project C affects not only the piping of hot/cold water but also the design of the lateral sewer line. Moving the lateral sewer line to the other side of the room means that it has to be connected to the main sewer line with an additional piece running underneath the building. Adding this extra connection means that the contractor in charge of soil work now has additional work to carry out on the foundation, which increases the cost of the project.

Finally, even though the washer/dryer unit in Project C is in the same location (it is only turned 90°), this also has a critical impact on the project. A worker with a special tool is needed to create the hole in the wall for the exhaust outlet of the dryer. In Project C, the drawings for the location of the hole were not updated before they were sent to the worker. This means that the hole was placed in the wrong location. This was discovered only two weeks later when the washer/dryer unit arrived and was test-fitted. However, the worker with the special tool had a long lead time and could not come out to the site to rectify the problem, which led to a one-month delay in the project. This resulted in the customer having to reimburse tenants one month of rent, since the move-in date was postponed.

The example presented above shows that the addition of the washer/dryer caused a chain reaction of variation in other technical systems, first, in the placement of the bathtub, which then induced a change in the hinge design of the washer/dryer itself. Furthermore, all the changes to the primary technical systems had a significant impact on multiple business-critical activities in secondary engineering. Thus, both cross-functional and cross-value-chain variances have been identified, and the first criteria had been met. Whether or not the variance in the bath fixture requires a critical architecture decision then depends on the second criterion: does there exist a potential to mitigate the variance by decoupling or clarifying system dependencies? This question is addressed in the third step of the CAM method as described in the next section.

4.1.3. Decision-Making on Cross-Functional Architecture

The illustrative nature of the mapping helps identify the key architecture decisions that could have been taken to eliminate the variance from the past. In the example described above, it is clear that there is no stable interface between the bath fixture and the washer/dryer. The illustration of the connection between the sub-systems indicates that there is a potential to clarify or decouple the dependency in the bathroom architecture. Figure 3 exemplifies this principle in a to-be scenario, in which a critical architecture decision is implemented. The decisions and effects labelled “3.1” and “3.2” in Figure 3 concern the following:

In Project B, space is reserved for the optional bathtub. The reserved space for the bathtub has stabilised the interface between the bath fixture and the textile care solution.

To keep the interface stable, the washer/dryer in Project B must be placed between the bath fixture and the wall. The fixed layout of the textile solution results in only one design of the hinge and, in addition, removes the risk of miscommunicating where the exhaust duct must go through the wall. The positive effects of the stable interface are also prevalent in the surrounding systems, which is described below.

Due to the stable placement of the washer/dryer, the toilet and sink combo do not have to move. This eliminates the need to change the placement of the door and, thus, the construction of a new wall element. Furthermore, the lateral sewer line can have a fixed position, which avoids the extra cost of soil work. Finally, the amount of longer piping needed as a result of moving the toilet, sink, and washer/dryer is now reduced to accommodate textile solutions only, thus reducing the cost of plumbing work.

The introduction of a stable interface between these two solutions eliminates the variance in both the primary technical systems and the secondary engineering. It eliminates the variance both cross-functionally and across the full value chain.

In summary, this section showed how the proposed CAM methodology could be used to (1) model historical design data from previous projects and the relation to activities across the full value chain and across all functional disciplines, (2) analyse the CAM model to identify which architecture decisions are truly business-critical for the cost and lead time in ETO companies, and (3) illustrate how the nature of the modelling enables decision-making to mitigate the effects of design variance in an ETO context.

4.2. Case Study Results

This section describes the use of the CAM method in relation to the three selected systems in the case company. The results are organised according to three steps of the CAM method: modelling, analysing, and decision-making. The observed effects of applying the CAM method are outlined for the latter step.

4.2.1. Modelling the Fluid-Handling System

The equipment system modelled in the case study concerns the processing of the fluids used in the manufacturing process, as illustrated in Figure 4, which shows only three sub-systems and not all value-chain activities (the figure would be difficult to read with additional steps included). The system's functionality is simplified due to confidentiality. In Figure 4, the first sub-system is highlighted in the second column after the layout. The main function of this system is to store two different fluids. The next system's function is to dose a specific amount of fluids upon request. Lastly, a pipe rack system with flow meters and control valves sends out the fluids to a range of different equipment consumers at the other end of the facility. Critical areas of secondary engineering were mapped based on input from key stakeholders in the company. Concerning the overall layout of the system, the piping design and steel support of the building were mapped, which was carried out due to the heavy loads of the tanks as well as the considerable amount of piping interfacing with this system. Concerning the storage and dosing system, the commissioning processes were mapped due to the high amount of instrumentation found specifically on these pieces of equipment.

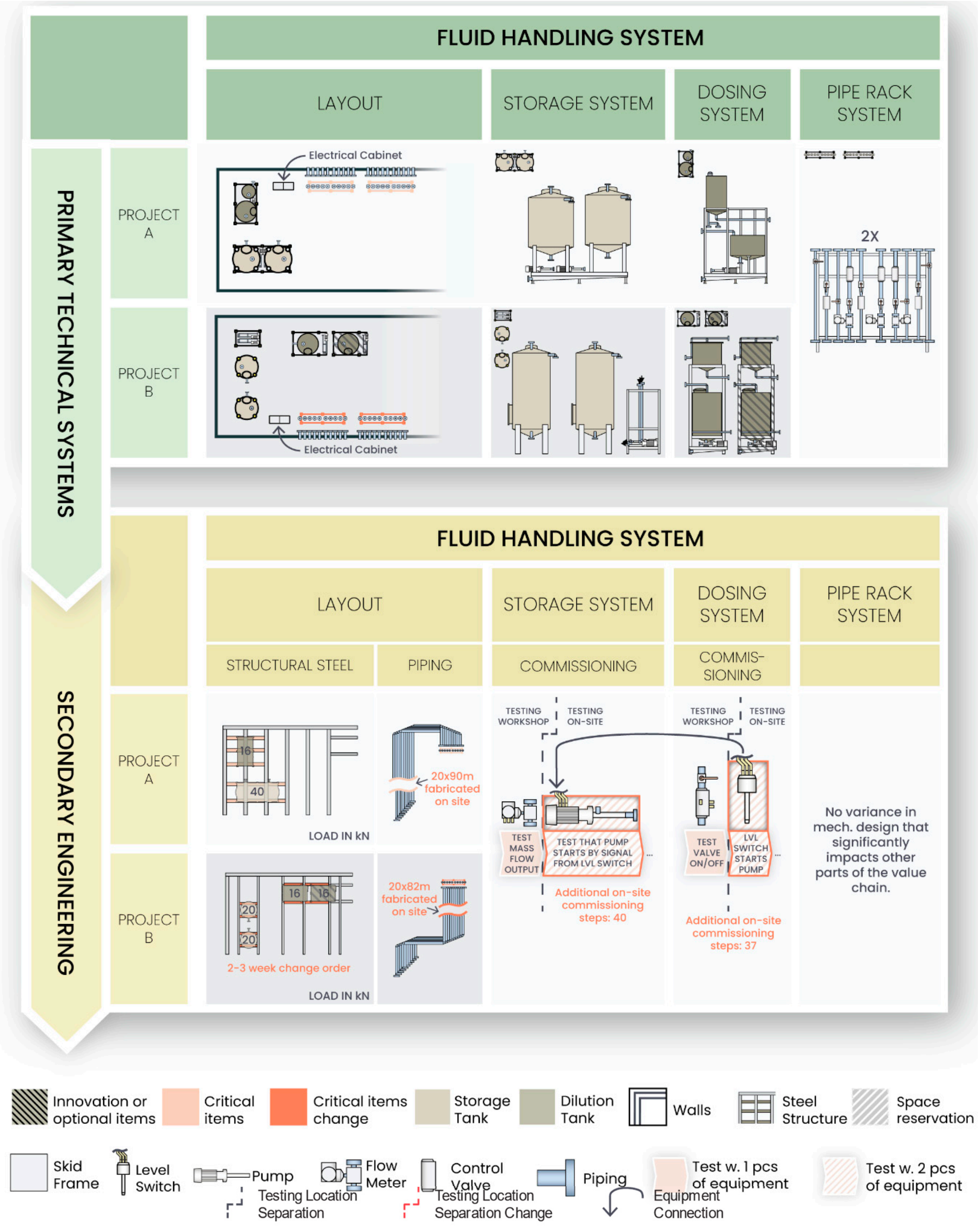

Figure 4. Fluid handling equipment mapped using the CAM method.

4.2.2. Analysing the Fluid-Handling System with the CAM Method

The first half of the mapping of the fluid-handling system shown in Figure 4 shows significant design differences between the two projects. The main difference in requirements between Projects A and B is that the latter requires the dosing of a second fluid. Thus, the sub-system for dosing has two sets of dosing units. Due to the extra unit, the overall system layout in Project B cannot be the same as in Project A. There is not enough space for two units located on the left wall of the room. Therefore, the dosing system is moved to the back wall of the room where the pipe rack units are located in Project A. This means that the pipe rack units are moved to the front wall of the room. These changes in the layout free up some room on the left wall.

Due to the narrow layout in Project A, the storage system has a compact design, with the pumps situated underneath the tanks and everything mounted on a common steel frame. Due to the changes in Project B, there is now vacant space along the left wall of the room. Therefore, the storage system now has its associated pumps mounted on a separate frame to the side of the tanks. While the pumps are now in a more accessible location, no specific project requirements explicitly called for this; thus, no additional benefits are achieved. Finally, the mechanical design of the pipe rack system is identical in the two projects.

The technical project managers commented that the design variance in the primary fluid system consumes considerable engineering hours. However, the impact on secondary engineering is much greater. This becomes clear when analysing the second half of the matrix. Three critical activities in the value chain are highlighted.

Looking at the impacts of the layout changes, the civil engineering of the building has to be considerably reworked. This stems only from the changes to the layout of the storage and dosing systems, since the loads of these systems require dedicated secondary beams underneath the tanks—unlike that of the pipe rack system.

The changes in placement mean that the statics of the steel structure must be re-engineered, and drawings must be updated and approved. The design of the steel structure is handled by external consultants, and, with the change management process that is required for external work, the new layout results in a two-to-three-week change order for civil engineering.

The second consequence of the layout changes concerns the pipe rack system. Since the pipe rack system is connected to consumers at the other end of the facility, changing its placement has a big influence on the piping that runs in between the rack and its consumers. The new placement means that the piping had to be routed along the right side of the facility instead of the left side, as it was in Project A. The final placement of the pipe rack was communicated at a late stage of the delivery. Thus, the CAD department did not have enough time to determine the routing of the piping during the design phase. This means that, instead of being able to design a routing in CAD for the piping to be pre-fabricated in a workshop, all 20 × 82 m of piping had to be fabricated on-site. This resulted in increased costs and a longer time to production.

The last consequence of the architectural choices concerns the commissioning of the storage and dosing systems. The mapping of the commissioning steps shows that a lot of the instrumentation of the storage system can only be tested once connected to the dosing system and vice versa. This is a challenge, since the two systems can only be connected once installed on-site. This means that the testing of critical instrumentation can only start late in the project. Furthermore, if problems are discovered during testing, they are harder to solve on-site. This ultimately leads to a longer commissioning time and, thus, a longer time to production for the company. The analysis revealed that the two systems are placed on separate frames due to the engineering team's desire for design flexibility. The consequences are summarised in Table 3.

Table 3. As-is scenario: historic architecture design variance and its impact on cross-functional and cross-value-chain activities.

Historic Architecture Design Variance	Critical Impact on Cost and Lead Time
Optional items not considered in standard layout => new placement of high-load items	Incorrect and late inputs to the civil department result in being unable to start civil engineering early and having to redo structural engineering often. The average change order impact was 2–3 weeks.
Frame construction of systems with high instrumentation complexity is optimised for layout flexibility and not commissioning	78% of commissioning steps are carried out on-site, while only 22% are carried out in the workshop. This results in increased travel costs and longer time-to-production.
Optional items not considered in standard layout => new placement of systems with high piping complexity	Late layout alignment implies that there is not time for routing piping in CAD, leading to routing and fabrication being carried out on-site. This results in increased installation costs and time by a factor of 2–3. It has also been shown to result in poorer fabrication quality due to sourcing unknown contractors locally.

As suggested in Table 3, the case highlights that there are relatively few but critical decisions in the fluids architecture that drive a high cost and lead time across different engineering disciplines and critical parts of the value chain. The decisions concern the layout and its flexibility. Architecture decisions have a significant influence on civil engineering and the amount of on-site construction work. There are also critical design choices related to the equipment itself that have a significant impact on the commissioning and installation process.

A similar improvement potential was found in the other two case systems. The analysis of System 2 revealed that only four (but significant) equipment changes resulted in civil contractor change orders, representing more than 12% of the total budget overrun. This is in addition to the internal engineering hours spent during the execution phase. The analysis of System 3 showed how the same two design parameters changed in every project. The influence these changes had on the functional design was not sufficiently documented, which meant that the process engineers were unable to troubleshoot the equipment efficiently during the start-up phase. The process engineers were delayed by 6% of the total project timeline. The findings from the analyses of Systems 2 and 3 are similar to those of System 1 (fluids); however, the details of these systems are not further disclosed due to confidentiality.

4.2.3. Critical Fluid-Handling System Architecture Decisions Based on the CAM Method

In the last part of the case study, the company explored solutions that would decouple and clarify the dependencies between the equipment design and the affected parts of the value chain. The final proposal is shown in Figure 5. The proposal was chosen based on its potential impact on cost and lead time. The figure shows a tweaked design of the fluid-handling system that has the same variety in project requirements but that significantly reduces the impacts of design variance.

As seen in Figure 5, the first change to the system architecture is the addition of a shared steel frame on which the equipment is mounted. First, this simplifies the interface towards civil engineering. Even if the sub-systems are moved around on the frame, the load points will remain the same and, therefore, will not affect the steel structure. The extra weight of the added frame only slightly increases the cost of the steel structure. This cost is far outweighed by the mitigation of the two-to-three-week change order. The commissioning process has the added benefit of having the storage and dosing equipment mounted on the same frame. Having the equipment assembled in its final layout in the workshop allows the company to run wiring to the instrumentation and connect it to the electrical cabinet. This, in turn, enables the company to run many more tests in the workshop before installing the equipment on-site. Ultimately, this gives the company the potential to reduce the number of commissioning steps carried out on-site.

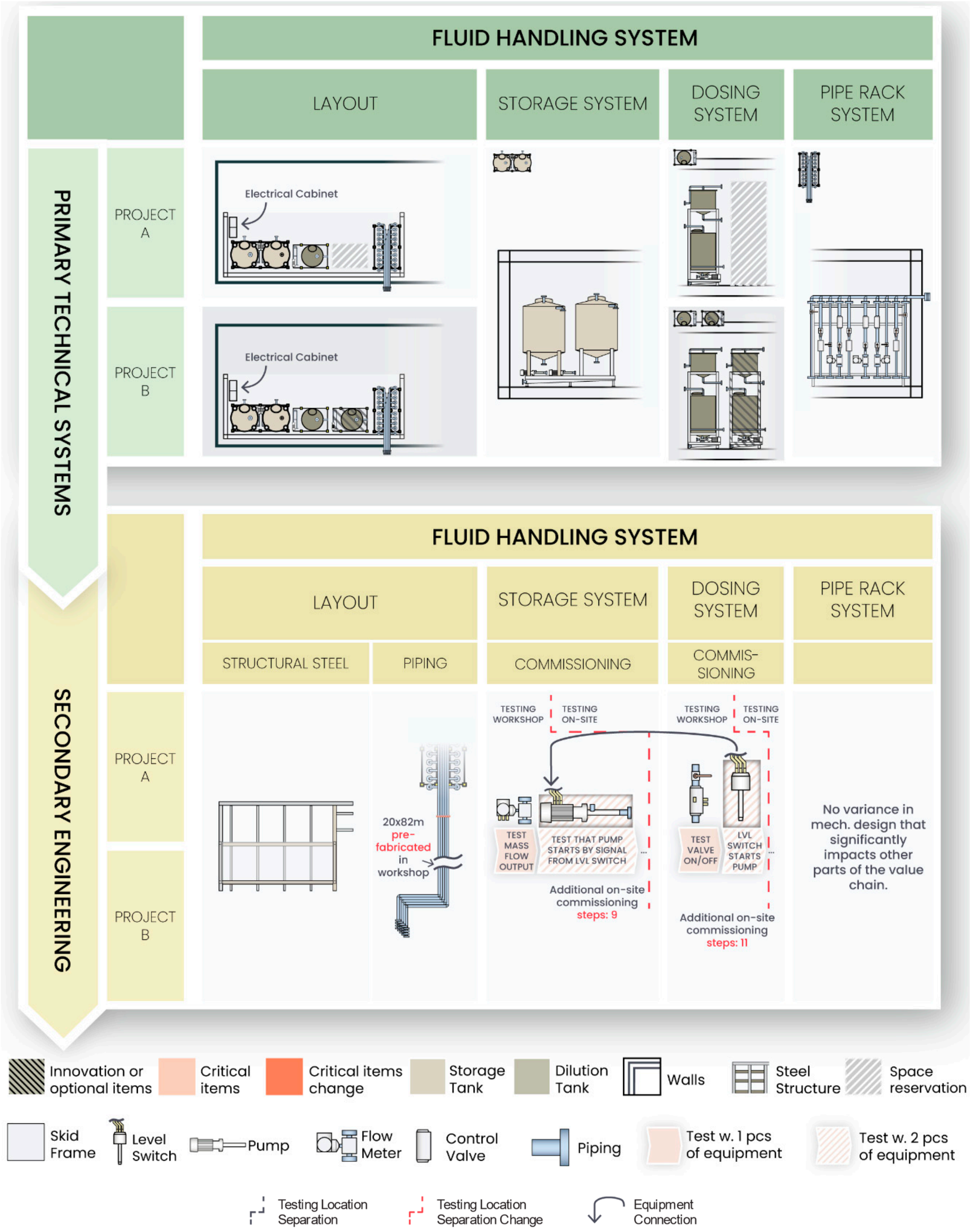

Figure 5. To-be scenario for fluid-handling equipment illustrated with the CAM method.

The second architecture decision is to reserve space for the optional dosing unit from Project B. Project A could be made slightly cheaper by not reserving the space. However, by reserving the space for the unit, the layout interface to the neighbouring units is clarified. This means that the placement of the pipe rack units can be standardised. Having the pipe rack units placed on the right side of the frame allows the piping to exit the room in the same place in both projects. Therefore, the subsequent pipe routing can be the same across projects. Standard pipe routing allows for pre-fabricating, which saves critical time and on-site construction work costs.

4.2.4. Evaluation of the Proposed Method

The findings show that changing or standardising relatively few but critical decisions in the fluid-handling system's architecture can result in savings due to the mitigation of change orders and moving working hours from the construction site to the fabrication workshop. Crucially, the potential reductions stem from both cross-functional and cross-value-chain activities such as civil engineering, and commissioning by electrical and process engineering, as well as installation work by contractors. The focus on a few decisions should provide a greater potential for the successful governance of the architecture, as argued by Løkkegaard et al. [11].

All the potential benefits were not fully realised during the study, as such projects normally take more than five years to fully implement, according to the project managers of the case company. However, significant implementation was still undertaken by the engineering management team as a consequence of the study's results. This includes resources being invested by the company in further technical due diligence and the conceptualisation of the proposed architecture decisions, in addition to contacting suppliers to investigate the manufacturability of the solution. Furthermore, a new position was created in the company for the overall strategy of equipment architecture: Head of Modularisation and Standardisation. This person is also a member of the engineering management team. Both initiatives constitute steps towards implementing the identified improvement opportunities. The strategies implemented by the management team substantiated the efficacy of the CAM method that was investigated in this study. Table 4 summarises these benefits for Case 1.

Table 4. Case company implementation towards initiatives.

Implementation Area	Action
Managerial	Creation of a new position for "Head of Standardisation and Modularisation"
Technical Solution	Investing internal resources in further technical due diligence and conceptualisation of the architecture decisions

In addition to the implementation towards the initiatives at the present time, the potential benefits were evaluated. Employees were asked to provide estimates of the perceived benefits of the method. Table 5 summarises these benefits for Case 1.

Table 5. To-be scenario: business-critical architecture decisions and the potential reduction in cost and lead time for the critical cross-functional and cross-value-chain activities.

Critical Architecture Decisions	Potential Reduction of Cost and Lead Time
Mounting critical systems on a shared open container frame (this decision is critical in structural load and in instrumentation complexity)	Harmonised input to the civil department, allowing civil engineering to initiate critical path work earlier for a 10% reduction in total build time and a reduction of the risk of change orders to structural design
	76% of commissioning steps can be carried out in the workshop, while only 24% need to be carried out on-site, resulting in a faster time to production
Clustering and standardising placement systems with high piping complexity	Transferring fabrication hours 2:1 from site to a modern workshop for only ~30% of the pipe meters was estimated to reduce piping installation costs by nearly 60%, reducing the time to production and improving welding quality

While this improvement opportunity was not measured after implementation, the above estimates still demonstrate a significantly positive impact of the architecture decisions that were investigated. Had the company not used the CAM method, the company perceived it to be unlikely that they would have identified these architecture improvements. According to the company, the initiatives were only found because the full value chain was represented. Furthermore, the fact that the initiatives did not rely on comprehensive design re-use or plug-and-play principles meant that they were also compatible with the design flexibility needed in the plants.

5. Discussion and Conclusions

The business models of ETO companies are characterised by a need for a high degree of customisation and, thus, a high degree of product variance. Like other companies with a high product variance, determining which cross-functional and cross-value-chain activities are most significantly affected by the product variance is difficult. The product architecture literature has demonstrated that it is only when investigating business-critical dependencies [11] in the full value chain [12,13] and across all functional disciplines [56–58] that architecture decisions are governable and have a relevant impact on the business of ETO companies.

However, the literature reviewed in this paper shows that there is a gap in the available methodologies for successfully addressing such dependencies in an ETO context. To address this gap, this study developed the CAM method, which offers a more holistic approach to implementing modular architectures in ETO companies. The framework was tested in a case study involving three projects for major equipment systems in a manufacturing plant design company. The case study demonstrated that the CAM method can provide significant improvements in system performance, an installation time reduction, a faster time to production, and total cost reduction.

5.1. Implications for Research

Building on the existing literature, the CAM method provides an approach to structure an analysis of the impact of design variance on the cost and lead time of business-critical cross-functional and cross-value-chain elements. The efficacy of the proposed CAM method was supported by the case study of the three analysed systems. Specifically, the method was applied to data from three historical projects in an ETO company to address few but critical architecture decisions concerning significant improvement opportunities in the most business-critical value-chain activities and functional disciplines. These include improvements in civil engineering, commissioning activities, and installation processes, leading to reduced costs, increased quality, and the increased parallel execution of critical activities. The findings led to the initiation of further conceptualising the proposed initiatives along with management actions towards implementation in future projects.

The result of the study supports previous claims that prioritising architecture decisions in terms of their business criticality is crucial for successful product architectures. Furthermore, the CAM method adds to the notion of business criticality in that it expands the context to be cross-functional and cross-value-chain. This is relevant for future ETO research as the previous literature highlights these attributes as being particularly critical for ETO companies. In this context, the proposed approach for modelling architecture decisions provides researchers with a tool to support studies of the implementation phase of product architecture decisions. By providing a methodology for prioritising architecture decisions cross-functionally and across the value chain, this study fills the gap for tools and methods for finding relevant and governable architecture decisions for ETO companies, thereby advancing the existing research on this topic (e.g., Harlou [7], Krause [10], and Pakkanen [6]).

5.2. Implications for Practice

The CAM method can help practitioners who are initiating modular architecture thinking within the design processes of ETO companies engaged in large-scale, complex product development. This case study supports the idea that relatively few architecture decisions have the potential to significantly improve the business of an ETO company. It also supports the idea that these improvement opportunities can be identified by investigating design variance holistically across functional domains and across the full value chain. The fact that only a few key decisions drive the potential for improvement should provide practitioners with a stronger foundation for governing their implementation and thus also capitalising on the architecture efforts [12].

Finally, limiting the scope to only a few architecture decisions should help accommodate the high degree of design flexibility that is demanded by ETO companies. Not having to adhere to strict true-copy modules could help ETO companies maintain their value proposition of providing custom engineering while simultaneously harvesting significant benefits of architecture thinking.

5.3. Limitations and Future Research

As the study revealed, the methodology is highly dependent on the presence of specific competencies in the organisation in question, which is largely due to the reliance on company stakeholders to identify critical cross-functional and cross-value-chain elements, which should, therefore, be prioritised in the modelling. These aspects of the method could be further strengthened by including a clear financial analysis of the impact of design variance. This would allow for a more quantitative assessment of the impacts of product variety and the potential architecture decisions. The method could also be further operationalised by incorporating existing methods from literature that focus on specific parts of the value chain or functional areas, such as on commissioning services (e.g., Mueller et al. [14]), supply chain integration (e.g., Brosch et al. [28]), and the design of modular architectures for assembly (e.g., Halfmann et al. [29]).

While the use of the CAM method identified significant possible benefits for the company in question, it did not address any of the technical due diligence needed for the proposed architecture decisions, nor did it include any further conceptualisation of the proposals. Thus, the outputs of the projects cannot be considered final solutions. Rather, the outputs should be considered a "gross list" that requires further development and due diligence before it can be implemented. Finally, while the intended outcome was achieved, the method should be tested in more ETO companies to further support its validity.

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