HVLV ENGINEERING WITH MODULE SYSTEM(S), ETO AND LEAN DESIGN – STUDY ON PRACTITIONER INFORMATION NEEDS

Juuti, Tero Sakari (1);
Heikkinen, Teuvo (1);
Heino, Tero (2);
Graf, Ilari (3);
Tomberg, Juha-Pekka (3);
Oja, Hannu (4)

1: Tampere University;
2: Valmet Technologies Corp.;
3: Meyer Turku;
4: Konecranes Corp.

ABSTRACT

This research elaborates the engineering design of high value low volume (HVLV) artefacts (aka Capital goods, investment goods). Our goal is to describe what information needs the practitioners have when doing sales engineering and engineering in HVLV projects. The research approach uses Design Research Methodology with four company cases.

Our findings are that engineering design of HVLV artefacts reuses several module systems, module libraries, technology catalogues, engineering-to-order and variety of design support systems, configurators, design guidelines, parametric models and lean-based design reasoning patterns etc. This poses major challenges for the engineers; how to use all relevant information and how to find it from different IT-systems.

This study indicates that in HVLV context such engineering strategy is required, which guides and drives tactical and operational engineering decisions not only within a project delivery but across project deliveries. Operative and tactical engineering is done during the delivery project and value capture is not achieved in full potential if the engineering strategy is neglected or overruled. This is challenge for current modularisation and ETO-methods and tools.

Keywords: Product structuring, Product architecture, Design practice, Lean design, Large-scale engineering systems

Contact:
Juuti, Tero Sakari
Tampere University
Finland
tero.juuti@tuni.fi

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1 INTRODUCTION

High value low volume (HVLV) artefacts (aka Capital goods, investment goods, B2B) business is facing similar global competition as discrete manufacturing during last decades. The HVLV product or solution must have optimal process performance and capacity for customer need. The lifecycle and the total cost of ownership needs to be optimised. The delivery projects need to be cost efficient, deliver high quality solutions, meet customer expectations and requirements every time.

Discrete manufacturing and mass customisation is studied since -80´s in consumer goods context. The successful tools, methods and approaches are applied in HVLV context too. Standardisation, modularisation, configuration, platforms, knowledge-based engineering, design automation, lean thinking are also used in project business. The drivers behind platform-based approach are cost reduction, productivity of product development and shorten lead time (Andersen et al., 2022). HVLV context is studied from engineering-to-order (ETO) and configurator viewpoints and from lean and supply management viewpoints. This study focuses on the engineering design in HVLV context, and the research question is what are the information needs of the engineering practitioners in HVLV context? The scope of this study covers engineering work before and after customer contract in project delivery.

2 RESEARCH STRATEGY, METHODS AND ETHICS

The study is done using design research methodology (DRM) with research clarification and descriptive study steps. (Blessing and Chakrabarti, 2009). The engineering context is High Value Low Volume artefacts such as power plants and paper mills. The research clarification is done previously, and the research gap is context in which engineers need to operate with architecture-based approach (e.g., modularisation) and lean design flow. The aim of the Descriptive Study-1(DS-1) stage is to increase understanding how unique artefact is created both with architecture-based approach (e.g., modularisation) and lean design flow (e.g., design reasoning paths(s)). The focus in DS-1 is to identify key information needed when engineering Hybrid Products (i.e. artefact consisting of Module System(s) and Engineering-to-Order entities). State of art - type review is done on modularisation, module systems, ETO, configurators, design support, design automation and design reasoning paths. Over 100 potential papers were identified, out of which 36 contributed to this scope. The data collection, hypothesis and validation were conducted with engineering practitioners. The data collection from lead users is done according to ethical research guidelines. The lead users signed relevant documentation and all personal data is managed according to GDPR guidelines. The companies and the artefacts remain anonymous but some relevant information is described not to harm the generalisation of the research results. Lead users as practitioners were identified from different companies having experience with artefacts consisting of modularisation and ETO. In all cases the technical system was perceived as unique artefact, and it was offered and delivered as a project delivery. The selection criteria were that they have also some experiences with Module Systems or design reasoning paths.

The descriptive study with the data collection and validation was conducted with following steps:

1. Practitioner A with experience on both Modules Systems and ETO was interviewed regarding information needs.
2. Hypothesis was formulated describing all identified types of information needs from Sales-phase to Delivery-phase. Hypothesis consist of all rows visible in Tables 2, 3 and 4.
3. Hypothesis was reviewed with the practitioner A.
4. Updated hypothesis was presented to practitioner B and C in separate meeting and to practitioner D, E, F, G in a separate meeting. Each practitioner reviewed the validity of hypothesis and gave examples of their artefact, information types and engineering context during the meeting.
5. All the data from each meeting was collected into a table.
6. Each table and description of each information item was reviewed by the relevant practitioners.
7. Analysis was conducted and the main findings were summarised as results.

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3 STATE OF THE ART

"Whatever the object or system may be, designing is a human effort to connect functional and structural elements of an artifact, and architecture means a basic design approach to link a system's functional elements to its structural elements, and/or to cut and connect a system's structural elements (components or modules) of the system (Langlois and Robertson, 1992). Ulrich states that architectural decisions are linked to the overall performance of the firm (Ulrich, 1995). Fujimoto describes further the architecture-based approach not only as product architecture issue but also as an organisational capability, people and process issue (Fujimoto, 2007). His data is from Japanese car manufacturing industry using architecture approach together with Lean approach.

Lean approach in construction and in civil engineering is studied by Koskela (Koskela et al., 2002). The idea is to cost efficient and effective operations using Lean methods and tools along the sales-delivery process. Lean design with lean engineering flows seems to have similar properties in civil engineering as in engineering capital goods. Lean design and manufacturing can be achieved when product models and manufacturing models having relevant information are available. Adlin describes formalisation of information flows for Lean implementation and benefits of Coordinated Property Driven Development (Adlin, 2022). A design template model is also proposed (Goto et al., 2008). Design reuse is studied already in -90´s by (Duffy and Ferns, 1998) but the use of engineering information flows has not been strong enough on research agenda. Design reasoning paths are modelled by (Mämmelä et al., 2019) to enable technology valuation in early phase of development. The path describes in which order engineering decisions needs to be made. It supports productivity and aims to reduce iteration in engineering design.

Lean approach and waste types are studied in Engineering-to-order (ETO) context (Birkie et al., 2017; Birkie and Trucco, 2016; Jünge et al., 2021). ETO operations performance was sustained with the integrated lean implementation. It also helped in identifying early on causes of wastes at multiple later stages of the value chain and to reduce waste in transactional processes. Alfnes et al. studied systemic factors creating uncertainty in complex engineer-to-order supply chains (Alfnes et al., 2021). The lack of ETO context in supply chain research agenda in identified (Gosling and Naim, 2009a) and later Cannas et al. identify three major emerging themes in this field; 1) ETO definitions through conceptualisation of the engineering flows 2) strategies for decoupling positioning, design automation and engineering management in ETO situations; 3) applicability of lean within ETO situations (Cannas and Gosling, 2021).

Willner et al. propose four distinct archetypes of ETO (complex, basic, repeatable, and non-competitive). The authors identify set of standardization and automation strategies for different types of ETO products (Willner et al., 2016b). The procurement process is crucial to establishing conditions for success and is typically major source of concern for the supply chain and several contractual choices are needed in engineer-to-order supply chains. (Gosling et al., 2021, 2017, 2015) A multi-attribute negotiation approach is even suggested for defining specifications for custom products (Chen and Tseng, 2005).

ETO challenges do not limit to sales engineering, engineering nor supply chain, logistics and site operations need to be considered, too. Matt et al. highlights the role of efficient installation supply chain considering suppliers, which deliver their products to a building site for assembly. Finished parts should be transported to the construction site Just in Time (JIT) with short lead times and low stocks in the fabrication shop and on-site. (Matt et al., 2015) This is difficult to achieve if engineering work is just under way. Just in time specifications are considered in aircraft manufacturing industry (Buergin et al., 2018). The approach links the product configuration phase following an Engineer/Order-to-order fulfilment strategy to production planning steps. The planning procedure comprises planning steps for order assignments as well as phases for product specification regarding modules within specific categories.

Many approaches are considered to ease the engineering design work and even to transfer (at least part of) the work to salespeople. Different kind of design automation and design support systems are studied. The drivers behind platform-based approach in process industry manufacturing are cost reduction, productivity of product development and shorten lead time (Andersen et al., 2022). Design automatization (Willner et al., 2016a) and sales configurators are studied in ETO context. Challenges in using and implementing configurators is discussed (Kristjansdottir et al., 2018) and how to capture configuration knowledge and model it for the software is discussed in (Haug et al., 2012). Rule based

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design in ETO is suggested by Chavali et al. (Chavali et al., 2008). Configuration stages are suggested with a conceptual framework supporting postponing configuration and enabling the management of product specifications on different aggregation levels (Christensen et al., 2018). Also cost and benefit of product configurators in ETO companies is elaborated (Haug et al., 2019). The actual product, modularisation and product structure is studied in application of Modular Function Development in capital goods context (Kjeldgaard et al., 2022). Capital goods standardization programs decomposition aspects are already in an advanced state (Gepp et al., 2015) but the integration of components, modules or subsystems into a customer-specific solution as well as integration of engineering disciplines, life cycle phases and stakeholders are critical yet neglected aspects.
ETO is still dominant in capital goods, but companies are increasingly using more efficient approaches to produce all information of the unique artefact delivery in the project. Support for the partly configurable product is discussed and the role of Module System partitioning logic (the documentation elaborating why such modules, architecture and interfaces are specified) is emphasised (Pakkanen et al., 2021). Modularisation, module system(s) and configuration based on standard elements is well known in the literature, but the situation changes when the product is not fully configurable but contains ETO entities lacking e.g., configuration knowledge or all module variants are not developed in advance. Product management has been discussed in several publications, but little specific management support has been presented for managing partly configurable modular systems. By using the 1) design reasoning path(s), or 2) knowledge on Module Systems, or 3) Coordinated Property Driven Development, systematic-engineering-to-order approach could be enabled alongside the configure-to-order and engineering-to-order.

4 DATA

The different HVLV artefacts are treated as samples. In Table 1 basic information of the data is described.

Table 1. Basic information on artefacts, sales value and engineering costs.

Sample	Practitioner	Typical artefact sales value	Project specific engineering costs
1	A	MEUR 30 - 80	MEUR 1-3
2	B	MEUR 10 - 20	kEUR 100-1000
3	C	MEUR 4 - 8	kEUR 50-400
4	D, E, F, G	MEUR 600 - 1200	MEUR 5 -12

The meeting with practitioners had two sections, in the first section briefing on the hybrid products and partly configured products was given. Key concepts and their meaning were elaborated with practitioners. For example, different BOM-structures were presented (Sales BOM, Service BOM) to ensure joint understanding. In the second sections the hypothesis was presented to practitioners and their comments were documented. The hypothesis was presented to the practitioners based on following statement: Would it be valuable for you to have this information available when engineering HVLV artefact?
Figure 1. presents small portion of the all information documented on a table-format. Information type is in the first column, then example of that is in the second column. Lead users' comments are documented in third column and practitioner´s examples on fourth column. If fifth column has Y-indicator, the hypothesis was identified and valid by the practitioner. The data consists of three separate documents, each from one meeting.

HYPOTHESIS		PRACTITIONER VALIDATION		
INFORMATION	EXAMPLE	INFORMATION	EXAMPLE	VALID
Bill of materials (BOM) /Component list	Parts with item codes			Y
BOM-structures	SBOM,EBOM,MBOM	Logistics BOM, Spare BOM		Y
Item status	"as manufactured", "as commissioned", "as maintained" e.g. for retrofit	As maintained - needed	As built - drawings	Y
Cost structure, Cost calculation models	Item costs	Very important		Y
Pricing model	Cost estimation for RFQ/	Somehow needed		Y

Figure 1. Small snapshot of the data from practitioners B and C. White rows are for practitioner B and grey rows are for practitioner C.

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5 ANALYSIS

The data is analysed by comparing different samples and identifying similarities and differences. The findings are arranged in three sections. First findings on sales engineering and engineering design in delivery project is elaborated, then a variety of engineering modes are presented. Last, information needs with architecture- and flow-based engineering is discussed. The Table 2 elaborates basic information needs that are relevant in (any) project delivery. These information types provide some support for engineering productivity.

Table 2. Basic information needs when engineering HVLV artefact. Each sample artefact has separate column. Validated information need in each sample is marked with ■.

Sales engineering and engineering design in delivery project -	1	2	3	4
Bill of Materials (BOM) | SKU´s (stock keeping unit), Component lists, BOM structures: Sales BOM, Engineering BOM, Manufacturing BOM, Logistics BOM, Spare parts BOM, Service BOM	■	■	■	■
Delivery / Item status | as manufactured, as built, as commissioned, as maintained	■	■	■	■
Cost structure, Cost calculation models	■	■	■	■
Pricing model for quotation and for offer	■	■	■	■
Work breakdown structure for the project delivery, work effort estimations	■	■	■	■
Customer needs & requirements, Request for quotation (RFQ)	■	■	■	■
Artefact transformation calculation and optimisation models e.g., to determine critical design parameters regarding artefact performance and capacity	■	■	■	■
Artefact breakdown structure, Function structure, System decomposition	■	■	■	■
Artefact architecture & layout	■	■	■	■
Technology Catalogue | Agreed, known and proven technology solutions	■	■	■	■
3D-models with modifiable parameters, models for artefact dimensioning and support detail design (was perceived as "configuration")	■	■	■	■

The designer information needs regarding the entire sales-delivery process is gathered in the Table 2. Information items are on rows and cases (artifacts) are on the columns. All practitioners indicate the same basic information needs when designing artefact in delivery project. Depending on the artefact B2B-context, different lifecycle phases are emphasized and their BOM-structures as well as item status types ("as built", "as maintained"). Cost calculation and pricing models are needed to support the design. Some differences are identified on how cost calculation models are composed and how pricing model drives design towards certain, suboptimal solutions. The height/width ratio of the plant can be more important than the optimal use of footprint available, for example. This can lead to very expensive design solutions thus having major impact on the artefact cost or TCO. Project work effort estimations are needed to calculate the cost. They also constrain design effort to be used in the project. Technology catalogues are needed to reduce work effort and to manage design reuse from previous delivery projects. Different models with parameters are used in sales engineering phase and in engineering phase to calculate artefact performance and capacity and to do detail design.

Module Variant to Delivery, introduced earlier by Pakkanen et al., 2019, is identified also with the practitioners in Table 3. The engineering context with capital goods is such that typically all engineering is done within the project delivery. Separate R&D resources do not exist for the organisation. This means in practice that it is not feasible or possible to design all module variants beforehand. This is a big contrast to consumer goods and mass customisation where all module variants are designed for the module system beforehand. Another limiting factor is how well customer needs can be anticipated for the customer solution. In HVLV context customer has strong negotiation position. There is substantial risk for showstopper in offering phase if the company offers solutions only for the anticipated needs and does not react on e.g., customer specific standards.

Modular Engineering to Delivery is identified being relevant in case that the delivery specific engineering should not violate the module system(s), their architecture, interfaces, space reservations or partitioning logic. Samples 3 and 4 introduces the situation that delivery specific work (engineering, fitting, installation, assembly) is done on site without detail drawings. This is due lack of engineering resources in previous phases. Craft to Delivery can cause problems and rework because the craftsman does not necessarily have all relevant information at hand. It refers to industrial practice in which the craftsman does the detail design in situ, as well as installation and commissioning in some cases. For example, piping can reserve space allocated originally for electric cabins. Then either cabins or piping needs to be refitted resulting in rework, additional cost and delay.

Table 3. Engineering modes when engineering HVLV artefact. Each sample artefact has separate column 1-4. Validated information need in each sample is marked with ■.

Engineering modes within operative boundary conditions	1	2	3	4
Engineer To Delivery (with or without design reasoning path)	■	■	■	■
Configure To Delivery (from Module System)	■	■	■	■
Module variant to Delivery (Derive to Order/Delivery from Module System)	■	■	■	■
Modular Engineering to Delivery (Delivery specific solution conforming Module System product structuring principles)	■	■	■	■
Craft to Delivery (Detail design, fitting and installation takes place on site)	■	–	–	■

Table 4. Knowledge and information sources when engineering HVLV artefact with Module Systems and DRP- sections. Validated information need is marked with ■ per each sample artefact.

Sources of knowledge and information for reuse	1	2	3	4
Artefact delivery is based on several Module System(s)	■	–	■	■
Module Library | Generic Modules and Module Variants	■	■	■	■
Configuration Knowledge | Rules, constraints between modules	■	■	■	■
Interfaces	■	■	■	■
Module System Architecture & layout, space reservations	■	■	■	■
Module System Partitioning logic	■	■	■	■
Lean flows for module types (managed process flow from sales to commissioning)	■	■	■	■
Design Reasoning Path(s) |	■	■	■	■

Table 4 indicates that practitioners need knowledge and information from diverse sources. It does not indicate that this information is currently readily available. In Table 4, samples 2, 3 and 4 indicate that the artefact delivery consists of several Module Systems, modules from separate module library and configurators. In some cases, a set of lean flows are described to manage the process flow from sales to commissioning. Interfaces and space reservations are used to reduce the complexity in operations. Module System partitioning logic is relevant when Module Variant to Delivery mode is used. Similarly, Modular Engineering to Delivery mode also requires information from the Module System and design reasoning path(s).
The identified sources of knowledge and information reuse support engineering productivity. For example, if the salesperson can do some configuration, a lot of engineering can be reused without any engineering work. Practitioners raise vast amount of information and knowledge needs. It seems that new type of needs emerges when using architecture- and flow-based approaches together, especially when building artefact synthesis with both approaches.

6 RESULTS

In this study, similar information needs were identified, regardless of the type or extent of capital goods and Engineer-To-order -type. The need for information on customer needs, BOM-structures, cost and pricing calculations exists. Also, more detailed information is needed from the artefact; architecture, lay-out, system decomposition and function structure, for example.

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Another similarity is regarding the need to benefit modularisation e.g., Module systems and design reasoning paths. These two design paradigms are based on different approaches. Modularisation requires architecture descriptions whether it is open or closed architecture. This support design by reuse on module and component level. Design reasoning paths require dependency models and means to manage iteration. Reuse of design reasoning paths supports effectiveness and quality of the engineering work. The practitioners indicated design support need especially for combining two distinctive design paradigms. Need on effective and efficient synthesis with module system knowledge and design reasoning pattern knowledge is identified. This can be formulated to a research question: How to reach synthesis with modularisation and design reasoning path(s)?

The practitioners also indicated a need regarding the way how engineering should be done for each entity of the whole artefact. Common modes in consumer goods are Engineering to order, configure to order etc. Practitioners preferred changing the terms emphasising their engineering context as project delivery. Thus, their preference is to call them Craft to Delivery (CrtD), Engineering to Delivery (ETD), Modular Engineering to Delivery (METD), Module Variant to Delivery (MVTD) and Configure to Delivery (CTD).

The major difference between samples was the availability of several types of information for engineering the artefact and how that effect on design work. This is observed also within each artefact; different design entities were engineered and managed differently due to lack of information. The practitioners reported experience on achieving synthesis by using different combinations of technology catalogue solutions, module library information, architecture and interface information. Some product entities are designed with configurators, cost calculation models and module flow information. The need for module system partitioning logic and design reasoning path(s) is identified but this information is currently not available as it is tacit knowledge of e.g., chief engineers or product architect.

Craft to Delivery is indicated by the practitioners in two artefacts. Some of the detail design remains on site typically due to lack of engineering resources or due to "tricks of the trade" - a tradition how craftsmen operate at the site. This is raised as an issue as it occasionally leads to iteration and engineering at the site or in the artefact. This results easily in conflicts and delays in the project, sometimes even problems and surprises in commissioning phase.

A couple of management implications are noted, too. Modularisation can take place during the delivery project as no separate R&D resources exists. This results to stand alone modules lacking information regarding architecture, configuration and partitioning logic. The modularisation decisions are done on tactical (i.e. within the project) or on operational (i.e. individual decisions) level by several stakeholders and thus leading to non-optimal solutions. The practitioners indicate that such engineering strategy is required, which guides and drives tactical and operational engineering decisions not only within a project delivery but across project deliveries.

Table 4 indicates also new research needs for Design Science. Concepts such as product platform, architecture and reusable assets are quite abstract. Thus their explaining power is suffering and is not currently adequate to support research on more refined understanding and modelling of modularisation in HVLV context.

7 DISCUSSION

Research on ETO types, ETO modularisation and ETO configuration exists already (Gepp et al., 2015; Kjeldgaard et al., 2022; Kristjansdottir et al., 2018; Willner et al., 2016b). This study provides novel information on several engineering types used with partly configurable products and emphasise the practitioner world view in projecting business - configure-to-delivery rather than of configure-to-order, for example. The research question is what are the information needs of the practitioners in HVLV engineering context? The answer is with the tables 2, 3 and 4. If the artefact has no modularisation the Table 2 is the answer to research question. If the artefact consist of Module Systems or design reasoning paths are reused, the tables 2 and 3 provide further insight.

Research exists also on modularisation and product families. Research on artefacts composed with several module systems is quite rare. These findings extend the architecture dimension; the question is not only between integral and modular architecture. The context is such that engineering needs to manage both modular design areas and integral design areas during the project delivery together with several stakeholders. Engineering decisions are made also by the sales, customer, purchasing, suppliers etc. The synthesis and the interplay between integral and modular sections seems to be the challenge. In ETO context, it seems that engineering requires a lot of information also from customer, sales, purchasing, supply chain, manufacturing, logistics and site operations.

The results indicate stronger need on capturing and modelling design knowledge (Wang and Duffy, 2007), design reasoning patterns (Mämmelä et al., 2020), design decision sequences (Halonen et al., 2014), and design reasoning paths (Pakkanen et al., 2021). Cannas and Gosling defined the 'new product development improvement' for managing engineering and manufacturing in ETO context (Cannas and Gosling, 2021; Gosling and Naim, 2009). This can be now extended to study how practitioners use many information sources and knowledge assets (if available) when reaching for artefact synthesis within the project delivery without NPD. This study strengthens the observations regarding benefits of lean in capital goods (Birkie et al., 2017) and lean flows done by (Adlin, 2022; Jünge et al., 2021) and the practitioners reported good experiences having defined processes for different module flows.

The research process is made as transparent as possible. The researcher is familiar with the artefacts due to previous research projects with the companies and this provides such insight that is not easy to compensate by researcher from other research field. First hypothesis is co-created with practitioner who is very experienced with modularisation, Module Systems, ETO and artefact performance and capacity calculations. Having less experienced practitioner, the hypothesis would have been different. Therefore lead users are identified, to study state of the art in industry. The analysis and the results of the study are reviewed with the practitioners and approved. The first hypothesis is co-created with practitioner and the information needs are identified by using design decision sequences. The product information of the project delivery is analysed starting from the outcomes and documentation. From there analysis continued towards the beginning of the project sales. Other researchers can use the same approach and most probably end up with the same results.

This study suggests several research questions for the future from engineering point of view. The engineering context consist of several engineering modes and several assets for design reuse in addition to Engineering-to-Order. Challenge is in sales, sales engineering and in engineering phases. How to decide in sales phase which artefact entities should be engineered with CTD rather than ETD? How to optimise artefact capacity, performance, total cost of ownership (TCO) and other objectives in sales engineering phase? How to design ETO/ETD sections alongside several Module Systems? How to model artefact design process having Module Systems and Design Reasoning Patterns? Our future work focus on support for designing partly configurable solution based on module systems, ETO and lean approach.

8 CONCLUSION

This study is highlighting artefacts consisting of module systems, module libraries, technology catalogue etc. and gives further understanding on several engineering types used in HVLV industry. In such engineering context with hybrid products, the research needs to be directed towards how the whole artefact is designed using several engineering types, ETO/ETD as one of them. This brings also novel challenge to the modularisation processes and methods; How to plan which sections of the artefact should be fully configurable module systems, which sections needs to be modularised and where design support is developed for ETO/ETD-configuration (e.g. design reasoning paths)?

This study is relevant in such engineering contexts where both architecture-based and flow-based approaches are used for artefact synthesis. It may mean that these findings are relevant to not only the capital goods (HVLV) but also artefacts with lower sales price and higher production amounts per year.

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