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Decision Support Systems for Partly Configurable Products in High Variety Low Volume Context

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Abstract: High Variety Low Volume (HVLV) context sets novel requirements for the decision support environment. The coexistence of engineering-to-order or engineering-to-delivery design alongside modular and platform design necessitates the integration of multi-disciplinary models. This paper provides a comprehensive review of existing model-driven and simulation-driven decision support systems, aiming to identify pertinent directions for tailoring decision support systems to meet the needs of practitioners in sales and engineering phases within High Variety Low Volume (HVLV) projects. This study identifies the following development needs: 1) accessibility of data and results to a broader user base, 2) guidelines for interacting with the decision environment without specialized expertise, 3) real-time feedback to decision-making teams, 4) metrics to gauge the maturity level or reliability of the models and 5) change management of the dependency models and calculation models. These are the next steps toward supporting decision-making in complex engineering situations under time pressure.

Keywords: Decision Support System, Partly Configurable Product, Module Systems, Engineering to Delivery, High Variety Low Volume

1 Introduction

High-variety, low-volume (HVLV) artifacts and project businesses, also known as high-mix, low-volume operations, face comparable global competition to repetitive, low-variety, high-volume manufacturing. Optimizing performance, capacity, total cost of ownership, and affordable initial investment of these artifacts is crucial during the sales process and negotiations with stakeholders. These artifacts are partly configurable, combining engineer-to-order (ETO) and configure-to-order (CTO) design paradigms. An example is a 360-meter-long, 60-meter-wide cruise vessel with 23 decks produced as a one-off product. Such products consist of hundreds of predesigned, configurable passenger cabins and large customer-specific entities. The steel structure and hull are optimized for that specific ship, as well as the general arrangement, which sets the layout of each ship deck. The unique wow factors are, for example, the amusement park on top decks, the wall-climbing aft, and the ice-skating rink on deck 6. Facing fierce competition, sales delivery projects must be cost-efficient, deliver high-quality solutions, and consistently meet customer expectations and requirements. Discrete, repetitive manufacturing has been studied since the 1970s in the context of consumer goods, with decision-support tools, methods, and approaches evolving over decades. The HVLV industry entails complex, flexible, process-focused production systems for non-repetitive, to-order manufacturing (Barbosa and Azevedo, 2018; Mello et al., 2015). Moreover, the sales phase, characterized by intensive engineering efforts, requires streamlining. However, making well-informed early design decisions in this context is challenging due to vague design requirements and incomplete customer needs.

In such a scenario, decisions must consider diverse needs, including customer perception, technical feasibility, lifecycle implications, and supply chain impact. Computational modeling has not yet matured to compute such heterogeneous dimensions, termed "ilities" in systems engineering literature (McManus et al., 2007; Bertoni and Bertoni, 2019a). Nonetheless, researchers highlight the importance of model-based decision support systems to enhance engineers' and decision-makers awareness of value creation for customers and capture by manufacturers (Matschewsky et al., 2018). Rhodes and Ross (2016) underscore the importance of human-centric models facilitating informed decision-making and effective human-to-human interaction.

This paper reviews existing model-driven and simulation-driven decision support systems, aiming to develop customized systems for sales and engineering practitioners in HVLV projects. It outlines the theoretical background of developing partly configurable HVLV products, explores the role of meta-modeling in decision support systems, and discusses how researchers in Value Driven Design (VDD) have addressed this challenge. Section 4 presents the results of a systematic literature review focused on model-driven decision-making for engineering. Finally, Section 5 reflects on the challenges and opportunities for meta-modeling techniques and VDD in the context of large HVLV artifacts with multiple systems and technologies and a protracted feedback loop for verifying calculation and optimization models.

2 Research approach

The problem definition at the origin of this paper is based on a research clarification activity performed in collaboration with an international company developing, manufacturing, and delivering HVLV products. Such findings have been combined with previous research results encompassing the identification of design "ilities" in product and service design

(Bertoni and Bertoni, 2019b) and a systematic review of meta-modeling strategy for systems of systems. The core of the data collection activity performed in this paper consisted of a systematic review in the field of model-driven decision support systems in engineering. The review was performed in the SCOPUS database using the following research string:

"Model-driven decision" AND "support" OR "systems" OR " arena" OR "environment" OR "design" OR "engineering" OR "development"

The focus of the research was deliberately narrowed with the intention to consider only decision support systems that allow for user interaction in decision-making, meaning that computational systems making automated and autonomous decisions were excluded. Eighty-seven papers were selected through the research string, of which 44 were selected as relevant after reading the title, abstract, and conclusion. Finally, the 44 selected papers were further classified based on their industrial field of application, their expected users, and the presence of a graphical user interface. The papers classified in the field of Product and Systems Design were then further analyzed based on the availability of metrics evaluating model reliability, the inclusion of a focus on lifecycle management and change management, and on when the Decision Support System is intended to be used during the development process (using the product development stages defined by Ulrich and Eppinger, 2016, as classification criteria).

3 High variety-low volume context and partly configurable products

Adlin (Adlin et al., 2020) underscores the existence of diverse contexts beyond mass production, a notion further elaborated by Rudberg and Wikner (2004) in their delineation of Production Planning and Control (CODP) perspectives. They advocate for segregating engineering and production facets to enhance coordination within project deliveries. Capital-intensive goods often undergo partial specification during the sales phase, necessitating comprehensive customer engagement throughout the sales, engineering, and production processes (Powell et al., 2014). The iterative nature of negotiations during sales may trigger engineering modifications, often cascading into significant changes during delivery and across the supply chain. These changes, stemming from various product delivery or lifecycle phases, introduce intentional and unintentional variations. Managing variability is scrutinized from a manufacturing lens by Tomašević et al. (2021), who stress the strategic importance of distinguishing between necessary and unnecessary variability and buffering necessary variability efficiently.

Engineer-to-order (ETO) practices are approached from supply chain and coordination perspectives, with three pivotal phases—tendering, product development, and product realization—demanding meticulous coordination (Hicks et al., 2000). Efficiently coordinating engineering and production activities holds promise for enhancing ETO supply chain performance (Mello et al., 2015; Gosling and Naim, 2009). Some organizations opt to manage sales, engineering, and ETO manufacturing by developing configurable, customer-specific artifacts, blending engineer-to-order (ETO) and configure-to-order (CTO) design paradigms. Powell et al. (2014) advocate for lean product development principles, emphasizing stakeholder value to attain operational excellence in the ETO manufacturing. Various approaches, frameworks, and tools, such as modular candidates, model-based systems engineering, and solution space reduction, are proposed to apply modularization to the ETO context (Christensen and Mortensen, 2022; Haug et al., 2013; Levandowski et al., 2015; Rabe et al., 2015). The amalgamation of modular solutions with engineer-to-order practices presents a multifaceted problem from both qualitative and quantitative decision-making standpoints, necessitating a comprehensive approach to decision support.

4 Theoretical framework

4.1 Meta modeling as a decision support tool for HVLV Systems

Due to growing complexities and uncertainties in decision-making, model-driven support systems have become increasingly important for decision-makers (Li et al., 2010). The advent of new business models such as servitization, in which the companies use their products to sell outcomes as a service, presents novel challenges of critical decision-making for designers early in the conceptual phase of the product development cycle. The correlation between servitization and HVLV lies in their shared emphasis on customization, value delivery, innovation, and a customer-centric approach. Both concepts are strategic responses to market demands for unique, high-quality offerings that may not be achievable through mass production and generic services. There is a need for a holistic modeling framework for decision-making that can capture complex system dynamics, interrelationships, and interdependencies. If the HVLV systems are System of Systems (SoS), this adds another layer of complexity due to managerial, operational, and geographical interdependences. Designing SoS interfaces, integrating them, and ensuring their consistency and interoperability is challenging as each system is heterogeneous, independent, and has its own independent life cycle (Fakhfakh et al., 2020). Such issues call for a framework that allows the integration of SoS into design methods.

The utilization of metamodeling methods for optimizing simulation problems has experienced substantial growth in recent years. This expansion aims to facilitate more resilient and flexible decision-making, ultimately identifying the optimal scenario within the design space. Meta models, according to Mhenni et al. (2022), refer to a framework or representation that captures the relationships and interactions between different levels of models within a complex system. The meta-model focuses on managing and representing relevant information for various views of a system's properties. Developing a meta model of SoS in the context of systems engineering allows to address new design challenges as the meta model of SoS helps to understand the various aspects of the system of systems, be it decision making, process optimization, or overall improvement in real-world operational scenarios. Kinder et al. (2012) highlighted the dynamic nature of SoS, whose architecture tends to evolve during the operation (as also highlighted by Kilicay-Ergin et al., 2012). Therefore, it is important to represent these SoS configurations to better understand the system performance and its intricacies for decision-making. The meta-modeling also includes the concept of service configuration, which describes how a service is put under operation, including the participation of SoS stakeholders and the use of a set of features, functions, and systems.

Dridi et al., (2020) identified four key characteristics of a meta model, focusing on structure and interaction viewpoints. The viewpoint provides a specific representation or perspective that highlights certain aspects. It serves as a comprehensive lens through which the structured elements and dynamics of the system can be understood and effectively communicated. The characteristics of a meta model include hierarchical organization, where constituent systems in collection form SoS and may act as a subsystem to another higher-level system. Likewise, the goals can be organized hierarchically, and dynamic role interactions are facilitated through relationships like "Include" and "Extend". Meta models are enablers of interoperability and heterogeneity for the efficient sharing of roles and goals in a hierarchically organized SoS. The aim is to help in decision-making to maintain the consistency of interconnected data and information from different activities and managed by different information systems (Belkadi et al., 2012).

Recognizing the significance of meta-models these models have gained widespread application across diverse industries, including healthcare (Burke et al., 2013), aerospace (Someya et al., 2023), marine (Monperrus et al., 2008), automotive (Kirpes et al., 2019), and others.

4.2 Value Driven Design

The concept of "value" has been central in the domain of "value-driven design" (VDD), serving as a unifying principle to facilitate engineers' decision-making during multifaceted analyses. Coined by Collopy and Hollingsworth (2011) in the Journal of Aircraft, VDD encompasses methodologies and tools for design decision support that prioritize generated value over requirements, guiding trade-off resolutions in complex systems and ecosystems (Isaksson et al., 2013). VDD comprises two primary approaches to enhance awareness of customers' valuation of various capabilities relative to each other: deterministic optimization models and qualitative models. Deterministic optimization employs mathematical algorithms to identify the "optimal system solution" for maximizing a specified monetary function of value, such as Net Present Value and Surplus Value (see: Curran et al., 2010; Cheung et al., 2012). However, critiques have been raised regarding the reliance on monetary functions (Soban et al., 2012), advocating for more qualitative models. Concerns about the reliability of deterministic models, stemming from uncertainty and data scarcity, impede effective communication among decision-makers (Monceaux et al., 2014), necessitating the adoption of VDD models grounded in Multi-Attribute Decision Making to support early-stage system design. Examples include the EVOKE model (Bertoni et al., 2018) and the EVA model (Rondini et al., 2018), which was developed for decision-making in product service systems design.

Recent developments in VDD literature underscore the potential of leveraging technological advancements to access and analyze data from the usage phase, paving the way for more robust assessment models based on quantitative metrics rather than qualitative evaluations. While, initially, the application of data-driven approaches within the VDD framework lacked a cohesive methodology (Bertoni, 2018), recent advancements have led to proposals such as the Data-Driven Product-Service Systems Design and Delivery methodology (Sala et al., 2020), a process for iterative value model generation in engineering design (Bertoni and Bertoni, 2019), and a framework for data-driven design automation in product service systems design (Machchhar and Bertoni, 2021).

5 Overview of the decision support environments analyzed in the review

This section provides an overview of the major contribution of model-driven decision support systems in the field of engineering. The papers in the table have been clustered based on their focus areas, also indicating the presence or absence of a Graphical User Interface (GUI) for the decision-makers to interact with the decision support systems. As shown in Figure 1, the focus on Product and Service Design is the largest in the identified literature, with 14 out of 44 papers clustered in that area, followed by Industrial Operation and Management and Production. The presence of an interactive graphical interface is not predominant among the papers, but several examples are homogeneously distributed in the different categories with no particular difference caused by the expected users of the decision support systems (as visible on the right-hand side of Figure 1). The categorization of the papers has further focused on the category "Product and System Design" to investigate the main features of decision support systems that come closer to the area of application linked to the development of HVLV products. The complete list of papers dealing with product and system design, including the categorization, is available in Table 2.

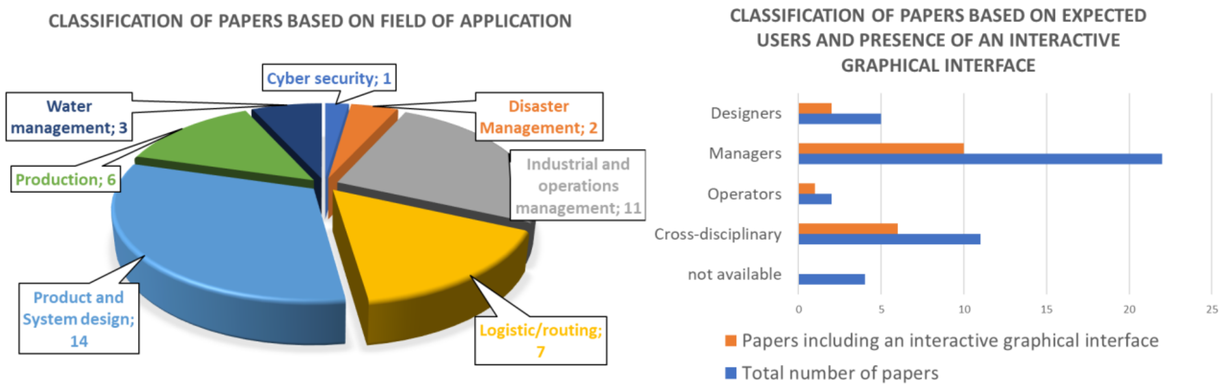

Figure 1. Classification of the papers identified in the systematic review based on the field of application (on the left) and on the expected users of the decision support environment (on the right) including the number of papers in which the decision support environment includes an interactive graphical interface (the orange line in the right figure).

The literature analysis shows that, in the field of industrial and operations management and production, decision support environments are predominantly developed and used by managers to optimize operations and production lines. A summary of these papers is provided in Table 1.

Table 1. List of the selected paper in the categories "Industrial and operation management" and "production" with the related classification criteria

Authors	Year	Focus area	Graphical user interface	Expected Users
Ainbinder I.; David Pinto G.; Rabinowitz G.	2019	Industrial and operations management	No	Managers
Alemany M.M.E.; Ortiz A.; Boza A.; Fuertes-Miquel V.S.	2015	Industrial and operations management	Yes	Managers
Jamalnia A.; Gong Y.; Govindan K.; Bourlakis M.; Mangla S.K.	2023	Industrial and operations management	No	Managers
Kovács Á.; Rádics J.P.; Kerényi G.	2017	Industrial and operations management	No	Operators
Muhammed K.; Farmani R.; Cisternas L.A.; Araya N.	2018	Industrial and operations management	Yes	Operators
Naseri N.; Ghiassi-Farrokhfal Y.; Ketter W.; Collins J.	2023	Industrial and operations management	No	Managers
Scheller F.; Burgenmeister B.; Kondziella H.; Kühne S.; Reichelt D.G.; Bruckner T.	2018	Industrial and operations management	Yes	Managers
Soykan B.; Erol S.	2015	Industrial and operations management	--	Managers
Zhen L.; He X.; Wang H.; Laporte G.; Tan Z.	2022	Industrial and operations management	Yes	Managers
Dinariyana A.A.B.; Deva P.P.; Ariana I.M.; Handani D.W.	2022	Industrial and operations managment	Yes	Managers
Abd Rahman M.S.; Mohamad E.; Abdul Rahman A.A.	2020	Production	No	Managers
Ivatury V.M.K.; Bonsa K.B.	2022	Production	No	Managers
Kuik S.; Diong L.	2019 (b)	Production	No	Managers
Madetoja E.; Rouhiainen E.-K.; Tarvainen P.	2008	Production	Yes	Cross-disciplinary team
Pérez-Salazar M.R.; Aguilar-Lasserre A.A.; Cedillo-Campo M.G.; Posada-Gómez R.; del Moral-Argumedo M.J.; Hernández-González J.C.	2019	Production	No	Managers
Soares A.; Pimentel C.; Moura A.	2022	Production	--	Managers

Little evidence is shown about systems capable of integrating simulation models to design and develop forthcoming production lines or industrial operations. Such capability would be particularly relevant for HVLV products where little flexibility in optimizing operation is available once the product has been designed and delivered. A few examples of decision environment supporting cross-disciplinarity are presented in the field of disaster management and water management (Austero et al., 2018; Esmaili et al., 2016; Al-Jawad and Kalin, 2019; Lykkegaard et al., 2021). Although not linked to a product development perspective, they provide good examples of how an interactive environment in the case of multi-disciplinary decision-making can be designed to anticipate the dynamics of operations and enhance the system-level design.

In the domain of product and service design, Power and Sharda (2007) underscored the imperative of harmonizing technical considerations with human behavioral factors within decision support systems (DSS). Their analysis delineated the interdependence of technical and behavioral research issues in DSS, challenging conventional paradigms. Subsequently, Xie (2010) proposed a DSS architecture integrating a user interface with a knowledge repository and simulations, facilitating a comprehensive evaluation of product reliability, availability, and maintenance across its lifecycle. Expanding upon this groundwork, Hertz et al. (2014) provided a comprehensive overview of tools supporting operational service delivery decisions, revealing limited practical adoption and inadequate support for strategic design decisions. They advocated for a DSS framework rooted in Unified Modeling Language (UML), featuring a user interface tailored for industrial field service network planning.

Table 2. Complete list of the selected papers in the "Product and System design" category with the classification criteria (NA=not applicable)

Authors	**Year**	**Stage of product development process**	**Expected users**	**Graphical user interface**	**Metrics for models' reliability**	**Inclusion of lifecycle-related aspects**
Bertoni A.; Larsson T.; Wall J.; Johansson Askling C.	2021	Conceptual design	Cross-disciplinary team	Yes	No	Yes
Bertoni M.; Wall J.; Bertoni A.	2018	Conceptual design	Cross-disciplinary team	Yes	No	Yes
Bibri S.E.	2021	Conceptual design	Designers	No	No	No
Hertz P.; Finke G.R.; Schönsleben P.; Cavalieri S.; Duchi A.	2014	Planning	Designers	Yes	Yes	Yes
Kloör B.; Monhof M.; Beverungen D.; Braäer S.	2018	Planning	Designers	Yes	No	Yes
Kuik S.; Diong L.	2019	Operations	Cross-disciplinary team	Yes	Yes	No
Lu J.; Yan Z.; Han J.; Zhang G.	2019	NA	NA	NA	NA	NA
Masood T.; Weston R.H.	2013	Planning	Cross-disciplinary team	No	NA	NA
Power D.J.; Sharda R.	2007	NA	NA	NA	No	No
Savrasovs M.; Yatskiv Jackiva I.; Tolujevs J.; Jackson I.	2022	Conceptual design	Cross-disciplinary team	No	Yes	No
Song Y.; Thatcher D.; Li Q.; McHugh T.; Wu P.	2021	NA	NA	Yes	NA	NA
Wall J.; Bertoni M.; Larsson T.	2020	Conceptual design	Cross-disciplinary team	Yes	Yes	No
Wall J.; Bertoni M.; Larsson T.	2018	Conceptual design	Cross-disciplinary team	Yes	Yes	No
Xie C.	2010	Conceptual design	Cross-disciplinary team	No	Yes	Yes

In response to the discourse surrounding the Internet of Things (IoT), Lu et al. (2019) delved into the pivotal role of computational intelligence and data science in DSS, emphasizing the development of data-driven predictive analytical models, accounting for uncertainties to facilitate informed decision-making. Recent scholars have delved into diverse developmental contexts, ranging from forecasting the ramifications of airport infrastructure design (Savrasovs et al., 2021) to road infrastructure (Song et al., 2021) and smart city planning (Kumar et al., 2020). Within the realm of industrial manufacturing, model-driven approaches for DSS have emerged to navigate the complexities stemming from manufacturing servitization, leveraging the concept of "value-driven design" to streamline multi-dimensional analyses (Bertoni et al., 2021). Moreover, Klör et al. (2018) exemplified the design, implementation, and assessment of DSSs to facilitate human decision-making in repurposing used vehicle batteries. Their methodological framework integrated scenario simulation, a model-based management system, and expert surveys, facilitating informed decision-making in the design phase.

While Table 2 does not explicitly address the development of HVLV products, numerous entries within the Product and Service Design cluster discuss decision support systems in contexts closely aligned with HVLV product development phase (life before contract) and engineering to delivery-phase (life after contract). One aspect to consider is the models' size, complexity, and reuse. Notably, the concept of utilizing models within decision support systems as "boundary objects" to foster collaboration and problem-solving among diverse, cross-disciplinary design teams is recurrent. Existing literature emphasizes the creation of decision support systems that facilitate stakeholders' navigation and interpretation of data from simulations and qualitative assessments, particularly when information about prospective products or systems is fragmented or inconsistent. The significance of human interface design and model visualization emerges prominently, aiming to mitigate cognitive limitations and enhance the capacity of individuals to discern patterns and relationships within datasets (Bertoni et al., 2021, p. 2143).

6 Discussion about the findings

The development of HVLV products entails a distinctive array of challenges with nuanced similarities to various design contexts, particularly within the realm of systems engineering, as identified in the existing literature. The coexistence of engineering-to-order or engineering-to-delivery design alongside modular and platform design necessitates the integration of multi-disciplinary models. This challenge, well-documented in the literature on model-based systems engineering, underscores the imperative of employing multiple and diverse models to facilitate communication and data sharing. While not explicitly tailored to HVLV products, the concept of Value-Driven Design (VDD), accompanied by semi-qualitative value modeling and visualization techniques, emerges as a promising avenue for decision support systems in the realm of partially configurable HVLV products. Conceived initially to challenge the requirements-driven paradigm in system development, VDD prioritizes value maximization over mere requirement fulfillment to foster innovation. While customer requirements remain pivotal in engineering-to-order processes, opportunities exist for modularizing various configurations of HVLV products or within HVLV products. Recent research by Bertoni et al. (2021) proposes Model-Driven Product Service Systems rooted in VDD principles to formalize data-driven activities, thereby enhancing the consistency and reliability of decision-making models. Leveraging the concept of value and its visualization as a universal language facilitates early communication with customers and suppliers in conceptual design.

VDD theory provides a portfolio of different methods and tools to be deployed in the design stages of complex systems, however, it still falls short in delivering comprehensive guidelines for addressing the design of HVLV products. Derived from such insights and the literature analysis, the following challenges are identified as those to be targeted in further developing decision support systems for engineering HVLV products.

- **Enhancing data accessibility results in a broader user base**. The comprehensibility of the models plays a key role in guiding decision-making from a multi-disciplinary perspective. The expected users of the forthcoming decision support systems will have different backgrounds and industrial skills and will need to understand the modeling logic and rationale behind the obtained results.
- **Establishing guidelines for interacting with the decision environment without necessitating specialized expertise**. The analysis of the available literature on decision support systems highlights the benefit, especially in the design of products and systems, of the presence of a clear graphical interface allowing users to interact with the models, even without specialized expertise. Several examples emerged in the analysis, focusing on the planning and conceptual design stages of product and systems design (as shown in Table 2).
- **Providing real-time feedback to decision-making teams to preserve the models' efficacy as "boundary objects"**. The decision environment shall be perceived by decision-makers as a dynamic computational environment to run quick trade-off about future products and systems configurations. The absence of real-time feedback and results updates undermines the capability of the decision environment to be used as a boundary object around which multi-disciplinary discussion about future product configurations is performed.
- **Incorporating metrics to gauge the maturity level or reliability of the considered models.** Together with the possibility of having real-time updates of model results, the decision support system shall integrate some metrics to share the reliability of the underlying model calculation. Examples of systematic metrics for knowledge maturity are presented in the literature (e.g. Hertz et al, 2014, Wall et al., 2020) but those applications are sporadic, while most of the model validations analyzed in the review are based on qualitative expert feedback.
- **Lifecycle management of the decision support environment, especially managing the changes to the dependency models and calculation models**. The development of a decision support system for HVLV products

requires a consistent investment that needs to be justified by the possibility of "reuse" of such a system for future HVLV as well. An approach to managing decision support system update, maintenance, and customization for different contexts needs to be studied and introduced since the early stages of the decision support system design.

7 Conclusions

The paper provides a comprehensive review of existing model-driven and simulation-driven decision support systems, aiming to identify pertinent directions for tailoring decision support systems to meet the needs of practitioners in sales and engineering phases within High Variety Low Volume (HVLV) projects. The coexistence of embedded strategic decisions with module systems and engineering-to-deliver sets specific requirements for the decision support environment. The paper underlines the significance of existing literature in product and service design, particularly within the Value-Driven Design (VDD) domain, as a primary avenue for investigating decision support system development for HVLV products. Within this framework, the paper emphasizes the importance of accessibility and communication capabilities inherent in a decision-support environment. However, it is crucial to acknowledge the preliminary nature of this investigation, which presents certain limitations in the scope of literature analysis and lacks specific proposals for approaches to be verified and validated based on the outlined findings. Consequently, the paper should be considered a foundational step toward developing such approaches to stimulate scientific discourse and interdisciplinary collaboration across various fields.

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