Towards Agile Systems Engineering in Early Stage Design for Complex Naval Vessels

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Abstract: This paper presents an overview of methodological support to tackle the challenges of uncertain and complex requirements, amorphous procedures and increasing systems complexity in early stage naval vessels design. The findings show that methodological support is available through various separate methods such as the Ship Design Spiral, the Systems Engineering Vee model, Agile Development Methods and Agile Systems Architectures, but lack integration into a holistic method. To overcome this problem, a Multi Domain Matrix is introduced that integrates the several approaches by combining Process Architecture Design Structure Matrices and Product Architecture Design Structure Matrices. Furthermore an approach is proposed that combines activities of the Ship Design Spiral, the Systems Engineering Vee model and agile method Scrum with an Agile Systems Architecture Pattern applied to naval ship architecture. Thus, this paper contributes to a holistic methodology in naval ship design to address current and future challenges through Agile Systems Engineering.

Keywords: Agile Development Methods, Systems Engineering, Ship Design, MDM

1 Introduction

As products changed from mechanical products to digitized and networked systems, system complexity as well as lifecycle complexity increased (Graeßler and Oleff, 2022). This is particularly true for naval vessels that are highly integrated systems of systems that operate themselves in a dynamic system of systems in military operations. The economically driven trend of navies to demand a higher variety of capabilities derived from fewer numbers of naval vessels, accelerated the increase of systems complexity (Attkinson et al., 2020). Nowadays naval vessels design means to integrate a highly complex mobile system of systems alongside the pure ship design (Andrews, 2018).

Due to this change, traditional ship architectures and design spaces (Attkinson et al., 2020) as well as traditional methods of ship design (Andrews, 2018) increasingly fail to give methodological support for the design of complex naval vessels. The Design Spiral for ship design (Evans, 1959) has been the most widely used model of ship development since the 1950s (Papanikolaou, 2014). It still provides methodological support for simple ship development projects, but only an unreliable representation of the development system for complex ship developments (Pawling et al., 2017).

Since the operational environment of the systems to be developed is characterized by volatile, uncertain, complex, and ambiguous (VUCA) conditions in military operations (Whiteman, 1998) and the variety of mission options required for naval vessels is increasing as well (Bundeswehr, 2023), there is a need for agile systems. The "Naval Vision 2035+" of the Federal Armed Forces of Germany emphasizes the importance of adaptable capabilities and mission-adapted equipment in the future (Bundeswehr 2023). Beyond traditional approaches of ship development, new methodological approaches are needed to address uncertainty in the development phases (Agis, 2019).

Uncertainty and complexity are inherent challenges of ship development and constitute a "wicked problem" (Andrews, 2017). This means that the problem is not understood until a solution is formulated (Bottero et al., 2022). Therefore, ship development is largely based on lessons learned from existing ships and successful designs (Papanikolaou, 2014). Due to the ever-increasing need to integrate additional technologies, the use of physical reference systems in naval ship development has left the economically and technically feasible range (Atkinson et al., 2020). However, development without recourse to fundamental solutions would turn a difficult activity into an impossible one (Andrews, 2017).

Further challenges alongside the naval vessels design are (Dahlke and Schmelzer, 2023):

1. the need to handle increasing complexity and uncertainty in requirements.
2. the need to replace amorphous procedures in concept design and preliminary design.
3. the need to handle increasing numbers of subsystems and system complexity.

To address these challenges, this paper intends to give an overview of potential methodological support to tackle the challenges of uncertain and complex requirements, amorphous procedures and increasing systems complexity in early stage naval vessels design. Furthermore it intends to give a proposal towards a holistic methodological integration of available methods.

2 Methodological support for challenges of naval vessels design

The development of naval vessels is basically divided into four phases: concept design, preliminary design, contractual design, and detailed design (Gillmer 1975, Watson 1998, Papanikolaou 2014).The scope of this work includes the requirements definition (clarifying the task) and the concept design. This section gives a general overview about methods to tackle the challenges of uncertain and complex requirements, amorphous procedures and increasing systems complexity in early stage naval vessels design.

2.1 Traditional methodology of ship design

The Ship Design Spiral (SDS) by Evans (1959) has been the most widely used model of ship development since the 1950s. As shown in Figure 1, it describes the ship design process as sequential order of design steps, run through iteratively to determine ship dimensions and other properties (Papanikolaou, 2014).

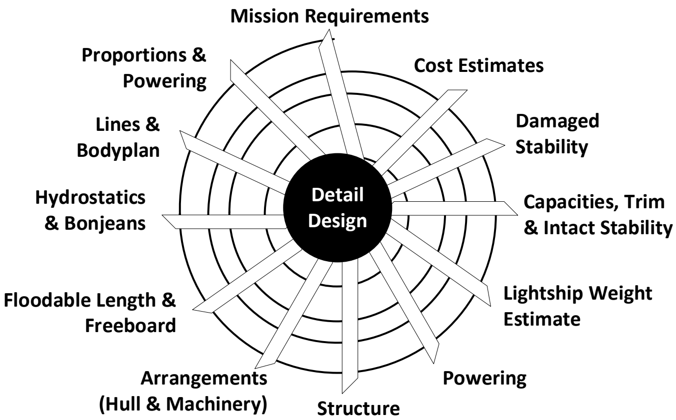

Figure 1. Ship Design Spiral (Evans 1959)

The requirements definition precedes the concept design of the SDS and is essentially based on a mission analysis as well as a threat analysis (Gillmer, 1975). It is supplemented in more recent approaches by additional aspects such as, economic requirements, manufacturing requirements, legal requirements and other requirements (Papanikolaou, 2014). According to the SDS requirements are considered as input variables to the spiral (Evans, 1959, Watson, 1998, Papanikolaou, 2014) and the ship development activities are run through the concept design in the first iteration. This is followed by two to three more iterations of all activities to generate the preliminary design, based on which the contractual design takes place (Papanikolaou, 2014). Subsequently, the detailed design takes place through continuous iteration of the activities. By iteratively going through the sequences of the development spiral, an increasing level of detail of the design is generated and the iterative and interactive nature of ship development is mapped. Over time, the spiral model has evolved and been adapted for the requirements of naval ship development by Watson (1998) and others.

The traditional spiral model of ship development is considered useful for properly developing ships as a technical solution using an appropriate and orthodox methodology (Bottero et al., 2022). It remains suitable for low-complexity development projects (Manfredi and Tirone, 2018), but still provides only an unreliable representation of the development process for complex ship designs (Pawling et al., 2017). Another major weakness of the traditional methodology is that stakeholder requirements are considered as fixed input at the beginning of the spiral in all variants of the spiral model (Bottero et al., 2022). Thus, the traditional methodology of naval ship development does not provide support in dealing with VUCA conditions of the development system or the increasing complexity of the system under development. However, the activities and results of the spiral model as well as its iterative nature are seen as an orthodox method for ship development and are considered as methodological support to replace amorphous procedures in early stage design.

2.2 Systems Engineering

Systems Engineering (SE) methodology includes numerous principles, such as systems thinking, system life cycle consideration, top-down principle, iterative development, multi-variant consideration, structured work and more (Stelzmann, 2011). Life cycle models of specific systems are highly relevant in the basic understanding of SE and are the basis for development process models. INCOSE (2015) does not propose a standard process model for the development of systems, but calls for the selection of sequential and iterative/incremental development processes according to the situation. The Vee model (see Figure 2) is often used to represent SE activities sequentially and is considered a reasonable representation. Integration, verification and validation planning on specific systems levels are essential to the Vee model.

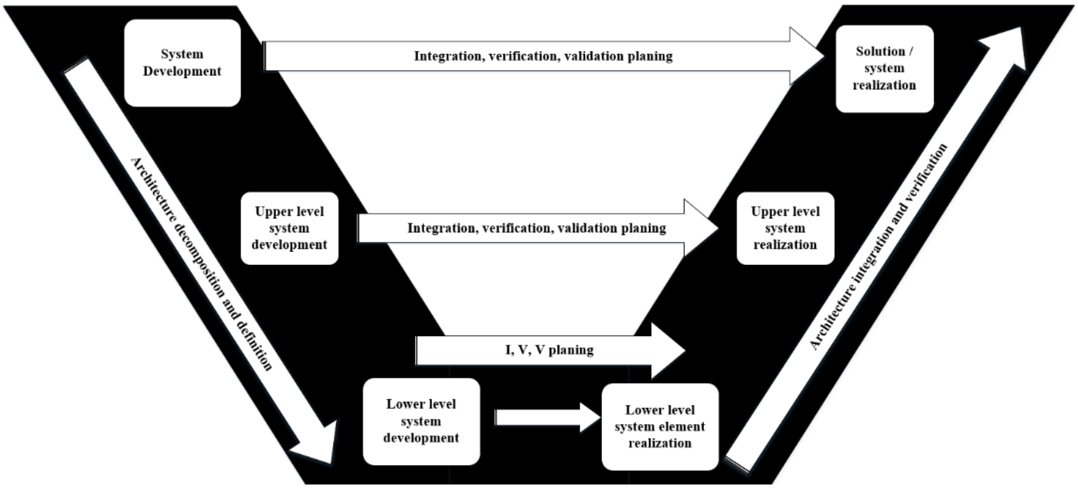

Figure 2. Vee model (INCOSE 2015)

The classical document-based SE approach has limitations, as information is difficult to keep up-to-date and consistent across multiple documents (Friedenthal et al., 2014), and the effort and error-proneness of changes are high (Madni and Purohit, 2019). Model-Based Systems Engineering (MBSE) gives support to overcome these limitations. MBSE is defined as "*[...] the formalized application of modeling to support system requirements, design, analysis, verification, and validation activities, beginning in the conceptual development phase and continuing through development and later life cycle phases*" (INCOSE, 2007). In MBSE, the system model becomes the primary artifact of the SE process. MBSE improves the ability to manage system complexity by allowing system models to be viewed from multiple perspectives and analyzing impacts of changes (INCOSE, 2015). To successfully use MBSE, the three pillars: language, method, and tool must be considered (Delligatti, 2013). De Saqui-Sannes et. al (2022) divide MBSE methods into four categories: Methods with conformance to SE standards, Methods with conformance to aeronautical standards, Methods associated with a specific modeling tool, and Methods M1 integrated with other Methods M2 (not developed for MBSE).

Due to the rising complexity of naval vessels and their requirements, SE methods with their requirements engineering and requirements management approaches gave methodological support since the 1970s (Thomas, 1981). The view of naval vessels as complex systems and the use of SE techniques to formalize the development phases are well recognized (Andrews, 1998). SE is used significantly in ship development to manage complexity and ensure requirements are met (Bottero et al., 2022). Manfredi and Tirone (2018) as well as Rouhan et al. (2022) present an MBSE approach for ship development considering the MBSE methodology as a support for the high complexity of the system under development as well as reference systems and architecture standards. A method integration approach to integrate SE methods with the SDS was made by Bottero et al. (2022), more than four decades after introducing SE to naval ship design (see Figure 3). Bottero (2022) introduces the relation between system development by iterations of SDS and verification and validation by SE techniques and concludes that the SDS is needed to "design in the right way", whereas SE is needed to "get the right design".

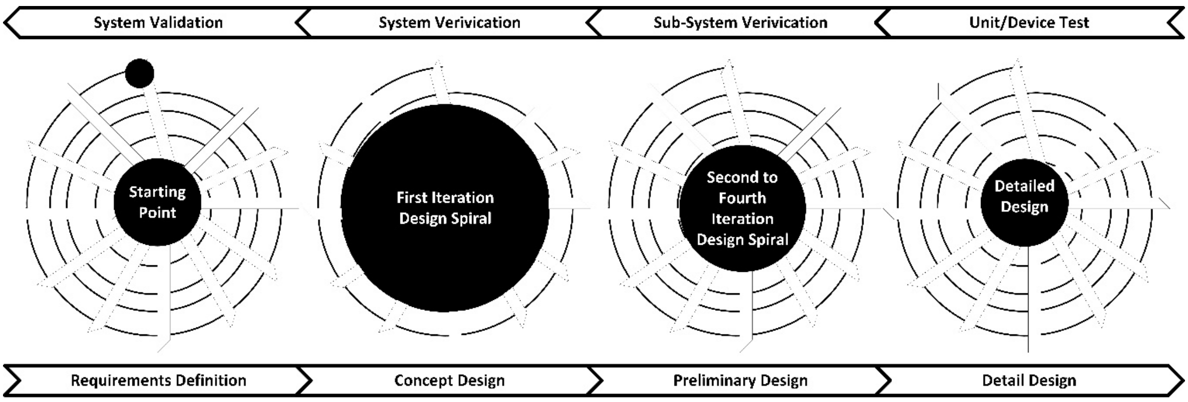

Figure 3. Design Spiral and Systems Engineering integration in accordance with Bottero et al. (2022)

Based on existing knowledge of the usage of SE and MBSE in naval ship development, SE and MBSE approaches will be considered as methodological support to replace amorphous procedures in concept design and preliminary design as well as support to handle increasing numbers of subsystems and system complexity.

2.3 Agile Development Methods for mechatronic products

Agile methods have established themselves as methodological support for product development of mechatronic systems under volatile, uncertain, complex, and ambiguous (VUCA) conditions and are gaining increasing importance (Nicklas et al., 2021). Volatility refers to unstable change that is frequent and sometimes unpredictable. Uncertainty refers to a lack of knowledge about the significance of ramifications of an event. Complexity relates to the degree of interconnected parts, forming an elaborate network and ambiguity describes the lack of knowledge of cause and effect connection (Benett and Lemoine, 2014). Böhmer et al. (2015) define agility as "*[...] the ability to react constantly and quickly to expected and unexpected changes in a dynamic environment and to use these changes (if possible) as an advantage*".

As Scrum is still the most frequently used agile method (Nicklas et al. 2021), the basic framework of Scrum according to Schwaber and Sutherland (2020) is described further as exemplary agile method. It is deliberately kept incomplete and allows additional processes, techniques and methods to be used within the framework. Scrum is based on the fundamental concept of Empiricism and Lean Thinking. Complex problems are broken down into transparent sub-problems and worked on in iterations by a self-organized development team of ten or less persons. The result of each iteration is a valuable part/product that is reviewed and thus provides information for possible adjustments. This approach enables decisions to be made on the basis of observations, knowledge to be gained from experience and waste to be reduced by focusing on what is essential. The Scrum framework is based on five events, three artifacts and three roles, which are briefly explained in Table 1. The interaction of the elements is depictured on the right site of Figure 4. A detailed explanation is given in the Scrum Guide by Schwaber and Sutherland (2020).

Table 1. Overview of SCRUM Elements (Schwaber and Sutherland 2020)

Scrum elements		Brief description
Arte-fact	Product Backlog	This artefact is an emergent list of what needs to be done to improve the product.
	Sprint-Backlog	Artefact, that represents the Sprint Goal and the set of items selected for the Sprint.
	Increment	A usable, additive and verified concrete step towards the Product Goal.
Events	Sprint	Fixed length events of one month or less to progress towards the product goal.
	Sprint Planning	Initial event to lay out work to be performed in the sprint.
	Daily Scrum	Daily 15 minute event to inspect progress towards the Sprint Goal and adapt work.
	Sprint Review	Final event of a Sprint, to inspect the outcome and determine future adaptions.
	Sprint Retrospective	Event to plan ways to increase quality and effectiveness of work.
Roles	Scrum Master	The person, accountable for establishing Scrum and help everyone understanding it.
	Product Owner	The person, accountable for maximizing the value of the product.
	Developer	The people in the Scrum team, that create the usable increment in each Sprint.

The benefits and challenges of agile development methods in ship design were explored by Castelle et al. (2019). Due to the findings, agile methods will be considered as methodological support to handle increasing complexity and uncertainty in requirements by reacting constantly and quickly to expected and unexpected changes and to use change as an advantage.

2.4 Agile Systems Engineering

Agile SE derives from the need for effective SE in the face of uncontrollable change. The intent is to enable effective response to an operational environment that is unpredictable, uncertain, risky, variable and constantly evolving (Dove and Schindel, 2019). In this context, agile SE understands agility as a capability of the system to be developed (product) and the development system (process). The necessary degree of agility in the development system and in the system to be developed depends on the respective operational development and operating environment, with product and process influencing each other (Dove and LaBarge, 2014b). Non-agile systems inhibit agility of the process and vice versa (Dove and Schindel, 2019). Agile process architectures strongly depend on the Agile Development Methods introduced in chapter 2.3. Hybrids of MBSE and agile methods have been introduced by Salehi and Wang (2019) in their Munich Agile MBSE Concept. Power et al. (2021) offer an approach that combines elements of MBSE with agile methods for complex systems of systems. Further experiences have been explored, with limitations identified in the scope of the agile SE development system (Stelzmann, 2011; Dove and LaBarge 2014b). Figure 4 shows an example of agile systems architectures and agile process architectures, as proposed by Dove and LaBarge (2014a, 2014b). The Agile SE Architecture Pattern consists of passive infrastructure that refers to standards and active infrastructure that enables module readiness, systems assembly and a module mix evolution (Dove and LaBarge, 2014a).

INCOSE (2015) identifies four core elements of the agile SE framework. Agile product architecture is intended to purposefully enable changes to the product (system) during development and manufacturing. Agile process architecture is intended to enable reconfiguration of goals, requirements, plans, and resources. The use of an empowered "product owner" to support comprehensive systems thinking and enable real-time decision making, as well as leveraging human performance factors that impact development, manufacturing, and customer satisfaction in an uncertain environment are also considered core elements of agile SE (INCOSE 2015). Agile product architectures have been extensively researched.

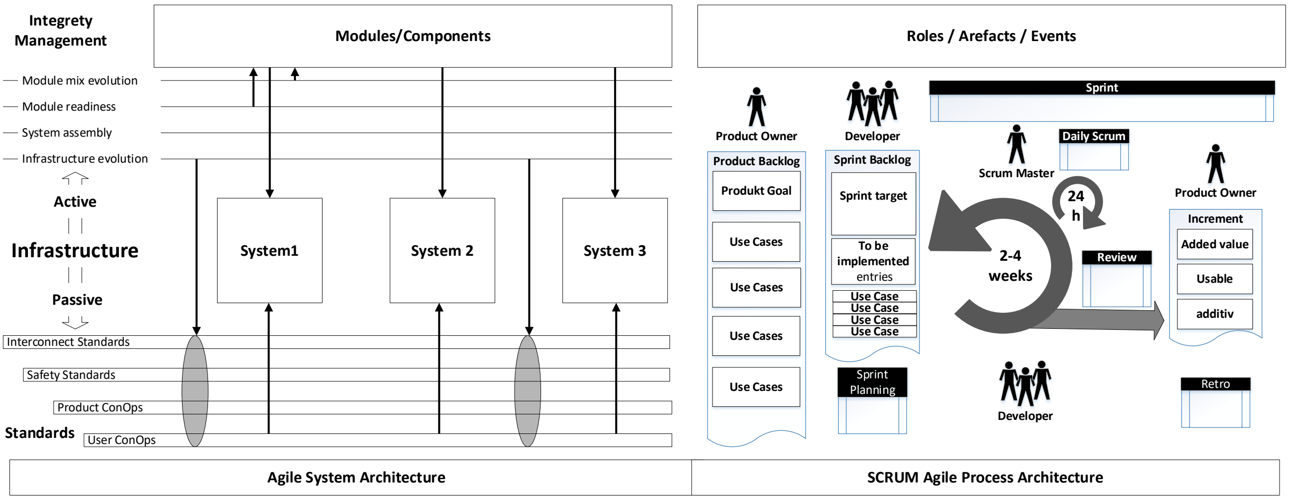

Figure 4. Agile SE (own representation in accordance with Dove and LaBarge 2014a and Schwaber and Sutherland 2020)

Due to the trade-off between rapidly changing capability requirements for naval ships and the high cost of development and production and the associated long life cycles, a demand for versatile and adaptable systems in navies can be stated (Atkinson et al., 2011). Considering the system under development as an agile system has also found application in naval ship development under the terms "versatile modular system" (Atkinson et al., 2011), "agile method for flexible ship architectures" (McCauley, 2016), "modular design for agility" (Christensen et al., 2018) and other general modularization approaches (Bello and Forero, 2020). Examples for the application of agile MBSE approaches to naval vessels design could not be found.

The consideration of an agile naval system to be developed as a coherent counterpart to the Agile Development Methods is a necessary constraint. Therefore the Agile Systems Architecture Pattern will be considered as methodological support to handle increasing complexity and uncertainty in requirements.

2.5 Research gap on ship design

As shown in chapter 2.1 to 2.4 several methodological support is introduced to naval ship design to overcome the current challenges of increasing complexity and uncertainty in requirements, amorphous procedures in concept design and preliminary design and the increasing numbers of subsystems as well as overall systems complexity. Unfortunately, most methods were introduced without integrating them into existing methodology support for naval vessels design to develop a holistic methodological support.

The activities and results of the SDS are still considered valid as methodological support for proper ship design and to overcome amorphous procedures but need further support to handle complex systems and VUCA conditions. The coexistence of SE methods and the SDS to overcome complexity issues was already stated in the 1980s by Thomas (1981) and Andrews (1986). Whereas the integration into a hybrid method between SDS and SE Vee model was just introduced by Bottero (2022) and is limited to SE activities of verification and validation. Agile methods and agile system architectures were already introduced separately to naval ship design as shown in chapter 2.3 and chapter 2.4. But there has not been an integration of agile processes and agile system architectures towards agile SE in naval ship design. The integration of agile methods and traditional ship design methodology is missing as well. Therefore, an integration of agile methods like Scrum and an Agile Systems Architecture Pattern with the SDS is a missing link.

Based on these findings it can be stated that there is only little related research approaches that tackle the challenge of holistic methodology support in naval vessels design. As meeting the challenges of increasing complexity and uncertainty in requirements, amorphous procedures in concept design and preliminary design and the increasing numbers of subsystems and overall system complexity (target area) requires consideration of an extensive methodological support (object area), there is a compelling need to integrate the required methodologies.

Therefore, this paper researches a possibility to integrate the several methodological support approaches needed to tackle current challenges in early stage naval vessels design.

3 MDM-Based Research Approach

As a first step to integrate the several methodological support approaches introduced to naval vessels design, this paper introduces a combined methodological support, that integrates the activities of SDS, SE and agile method Scrum as well as their possible inputs and outputs for agile architectural frameworks by using the Multi Domain Matrix (MDM) methodology by Eppinger and Browning (2012). In this paper, the MDM is not used to describe dependencies of elements of an existing system, but to prescribe possible interactions of the several activities and system architecture elements identified in chapter 2 within an integrated methodological support approach.

Figure 5 shows the basic structure of the MDM approach used in this paper to prescribe dependencies between the activities introduced by the several methods and their dependencies to the architectural framework of naval vessels. The basic starting point of the MDM are three Process Architecture Design Structure Matrices (DSM1-3) that represent the intra-element dependencies introduced by the activities of support approaches in chapter 2.1-2.3. Further starting point is the Product Architecture DSM (DSM4) that displays architectural intra-element dependencies of naval ship components on the level of main construction sections according to the German Naval Architecture Directory by analyzing the introduced naval vessels agile system architectures in chapter 2.4. These DSM (DSM1-4) are colored green in Figure 5.

To integrate the several support approaches, there are six Domain Mapping Matrices (DMM), mapping product architecture elements and SDS, SE and Scrum activities. These DMM (DMM5 – DMM10) are colored pink in figure 5 and represent proposed inter-process-product dependencies. The MDM also contains six Process Architecture DSM that prescribe the integration of inputs and outputs of activities from different methodological support approaches. These DSM (DSM11 – DSM16) are colored yellow in Figure 5.

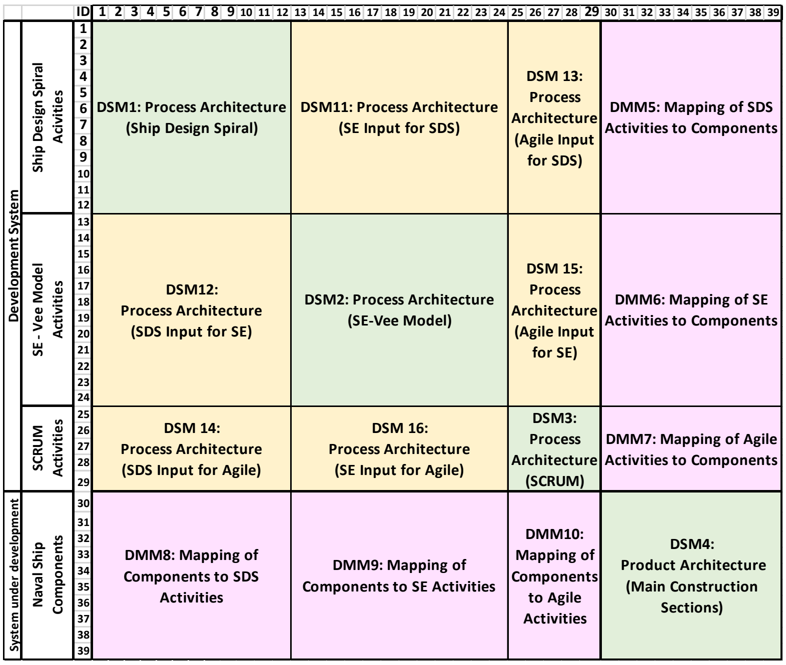

Figure 5. Stylized MDM structure to prescribe an integrated methodological support approach

4 Results

Figure 6 represents the methodological support approach introduced in this paper that integrates activities of SDS, the SE Vee model and agile method SCRUM as well as agile architectural frameworks by a binary MDM. The prescribed integration is fitted for the phases of concept design of complex naval vessels, which includes the first iteration of SDS (see chapter 2.1), the SE Vee Model activities to upper level system development and integration (see chapter 2.2) and is executed in the first Scrum Sprint (see chapter 2.3). Activities that are not performed during concept design are colored gray and are not taken into account. The Agile SE Architecture Pattern is represented on the highest level of main construction sections (MCS) of naval vessels (see chapter 2.4) to meet the system level in concept design. The results of the MDM are grouped into the ten DSM and six DMM introduced in chapter 3. For better understanding, the numbers are also depictured in Figure 6 and described in the following section. The DSM1-3 represent the starting point process DSM for the activities of SDS, the SE Vee model and Scrum. The activities within the separate methodological support approaches strongly rely on each other by input and output dependencies. During phases of concept design all activities are run through the first time. As a simplification it is assumed that activity n gives output to activity n+1 and all following activities n+x within its own DSM.

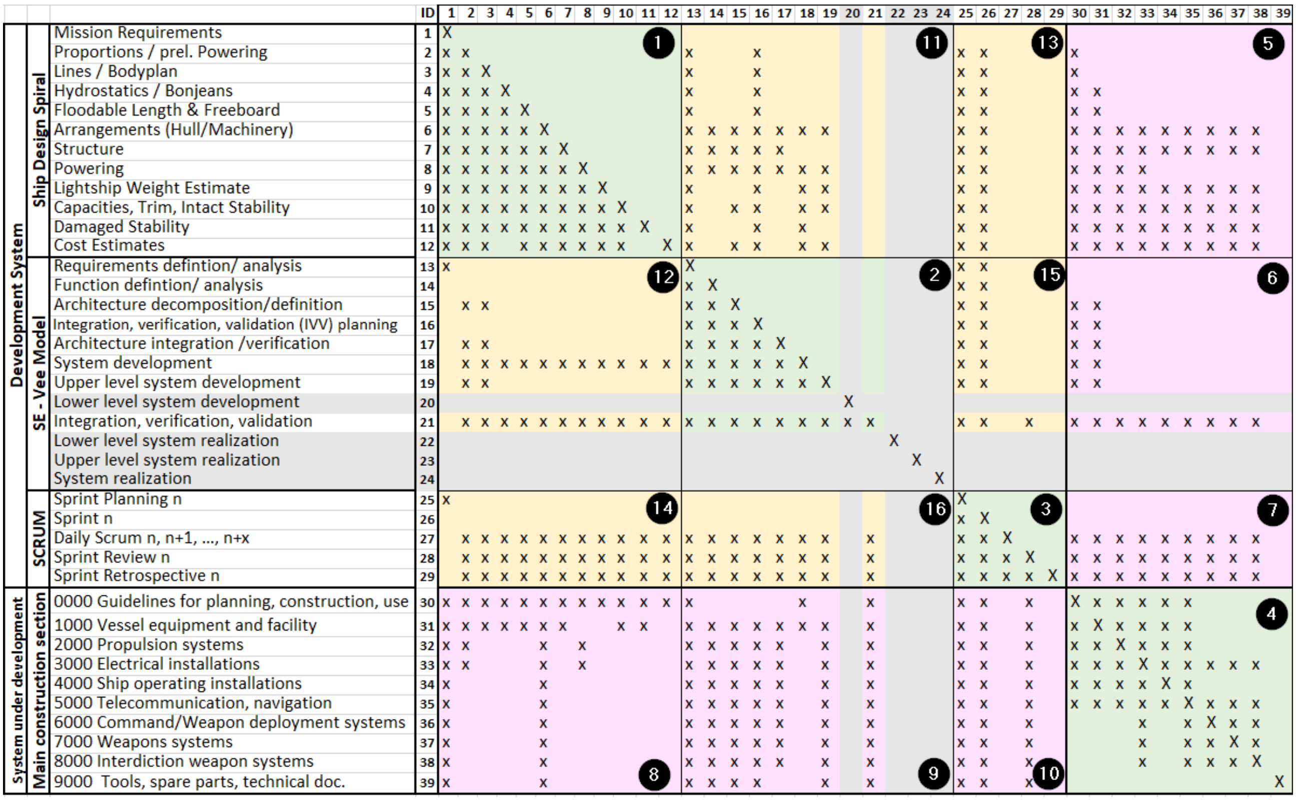

Figure 6. MDM-Representation of integrated methodological support approach for concept design of naval vessels

As stated in chapter 2.4, the possible degree of agility in the development system (process) and in the system to be developed (product) depend on each other. Therefore this paper suggests the integration of the Agile SE Architecture Pattern proposed by Dove and LaBarge (2014a) with the concept of Versatile Modular Systems (VMS) by Atkinson et al. (2011) and modularity in warships by Bello and Forero (2020). DSM4 shows the product architecture DSM for the transmission of the Agile SE Architecture Pattern to the main construction sections according to the German Naval Architecture Directory. A graphical representation through the fictitious example of Corvettes of the 130 BRAUNSCHWEIG class is shown in Figure 7. A strong dependency can be stated for MCS 0000 to 5000, which represent the passive infrastructure of the platform system. Another cluster are the dependencies of MCS 3000, 5000, 6000, 7000 and 8000 which represent the active infrastructure of the mission system. Interconnections between platform and mission system seem to be especially important in MCS 3000 and 5000.

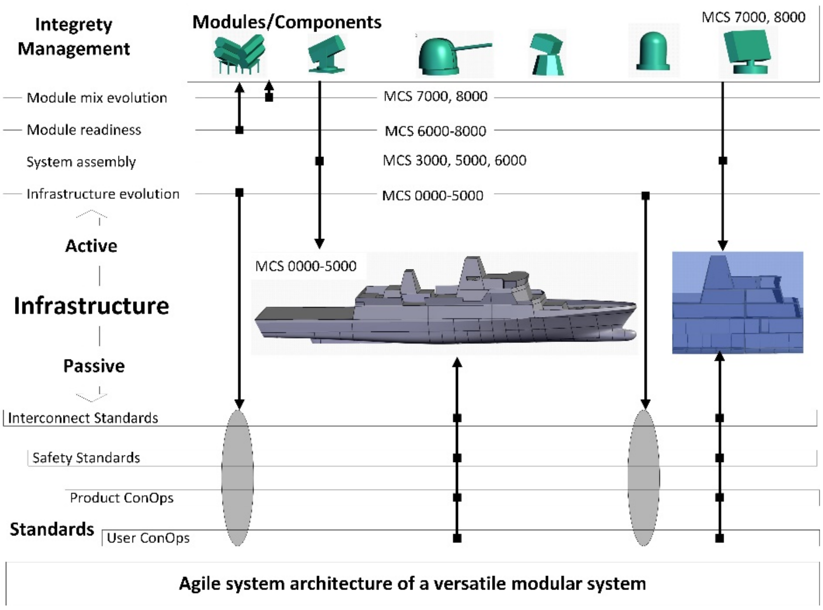

Figure 7. Agile Systems Architecture for a versatile modular system on fictional example of K130 Corvette

As a prerequisite to integrate the activities of the several methods in a useful way, their input and output relations with the systems architecture were described. The DMM8 displays that the activities of SDS produce major output for MCS 0000 and 1000, which contain ship theory results and the vessels general plan. Activities 2 and 8 also deliver output for MCS 2000 and 3000, whereas activities 1 and 6 produce output for all MCS. DMM9 indicates that SE activities strongly contribute to MCS 1000 – 9000. Whereas the agile activities may deliver output to all MCS, as shown in DMM10. During concept design, the activities 1-5 may be executed by only having preliminary results of MCS 0000 and 1000, as displayed in DMM5. Activities 6-12 may contribute from inputs of all MCS. DMM6 shows, that SE activities 13-19 may be conducted only by inputs from MCS 0000 and 1000, while activity 21 definitely needs previous results from all MCS. The first Sprint Panning and Sprint (activities 25 and 26) may be executed without previous results from MCS, while results are necessary preconditions for activities 27-29.

Based on the information provided by the DMMs, the activities were combined into an integrated methodological support approach as shown in DSM 11-16 and graphical represented in Figure 8. This approach executes activities of SDS and SE within the Scrum Framework. The definition of mission requirements (activity 1) represents the initial act of all activities and gives input to the Sprint Planning (activity 25). Within Sprint Planning (activity 25) the SE requirements definition and analysis (activity 13) as well as SE IVV planning (activity 16) is performed. DSM13 and DSM15 show that the Sprint Planning gives input to all other activities. Further activities of SDS and SE are executed within the Scrum event Sprint (activity 26). The synergetic combination of SDS and SE activities within the Sprint may be based on the provided information of the MDM and adapted to the current needs dedicated to the current Sprint. As shown in DSM11, especially SDS activities 6-12 may profit from further SE activities. DSM12 displays that SE activities 15, 17, 18, 19 and 21may get input from SDS activities. As shown in DSM14 and DSM16, the agile activities 27, 28 and 29 get input of all activities executed during the Sprint. The input of Daily Scrum to other activities during the Sprint is not shown, as this strongly depends on the specific project circumstances. The Sprint Review (activity 28) takes place at the end of every Sprint. The output of Sprint Review is only located as input to IVV (activity21), as the concept design is executed within one Sprint.

During design phases of preliminary design, the level of detail and the amount of work to be done is rising. As shown in chapter 2.1 the preliminary design needs two to three more iterations of the activities of SDS, which will take several Sprints and should be supported by more SE activities as well. Since the execution of SDS and SE activities for a higher level of detail need more time, the activities executed within the next sprint need to be selected during each Sprint Planning. Hence the input dependencies of agile activities 26 to 29 may vary within DSM14 and DSM16 from Sprint n+1 to n+x. The Sprint Review will also give more inputs to other activities within Sprint Planning n+1 to n+x. As the number of team members will exceed the recommended number of agile method Scrum (ten persons or less), the Scrum activities will have to be replaced by activities of scaled agile methods like Scaled Agile Framework (SAFe) or Scrum@Scale.

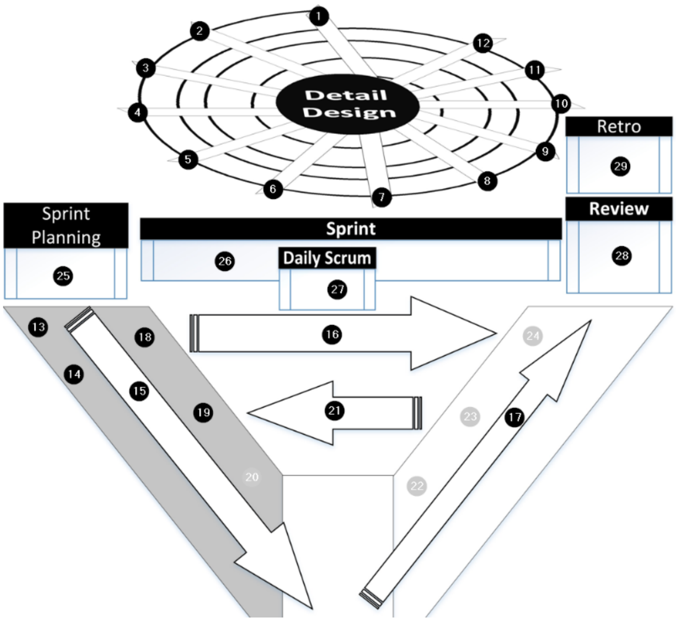

Figure 8. Graphical representation of integrated Agile, SDS and SE activities in concept design

5 Discussion

The application of a MDM-based research approach led to an integrated methodological support approach for naval vessels concept design that integrates the activities of SDS, the SE Vee model and agile Scrum activities as well as the transmission of an Agile Architecture Pattern. The MDM representation (Figure 6) shows that there are multiple dependencies between the integrated activities as well as process-product dependencies. The combination of inputs and outputs of activities from different methodologies is assumed to lead to better results than the singular execution. As shown by the product architecture DSM4, agile architectural frameworks may be implemented even in concept design on the level of MCS. Therefore, the proposed methodological support approach is suitable to close the identified research gap.

Although the results are suitable to close the research gap, there are several limitations. First of all, the support approach is based on dependencies identified by literature reviews and the authors knowledge of practical implementation to the field of naval vessels design. A field study to verify the benefits of the proposed integrated methodological support approach is currently taking place at a northern German shipyard group. Within this field study, the assumed dependencies shown in Figure 6 are to be validated and tailored to the practical needs. A data-driven approach using MDMs to manage and optimize dependencies in practical usage needs to be implemented.

Another limitation is the scope of the presented approach. The MDM presented in Figure 6 is fitted for the phase of naval vessels concept design, which only includes the first iteration of SDS, the SE Vee model activities up to upper level system development and the execution in one Scrum Sprint. The design phases of preliminary design will need two to three more SDS iterations, several Scrum Sprints and lower level system design and integration. As the level of details rises, the dependencies may shift and need to be rearranged for every Sprint. Furthermore, the agile method Scrum is only fitted for small development teams. As the size and amount of teams rise along the preliminary design, the activities of Scrum may be replaced by activities of scaled agile methods.

An additional limitation is the level of detail of the Agile Architecture Pattern presented. The architectural analysis on MCS-level only allows the differentiation of passive infrastructure of the platform system (MCS 0000 - 5000) and active infrastructure of the mission system (MCS 3000, 5000-8000). This level of detail might be enough for concept design, but needs to be decomposed to lower systems architecture levels, as construction section and main structural component or structural component during later design phases. An extension of the product architecture DSM will be necessary.

6 Conclusions

The key contribution of this paper is to show a possibility to integrate the several methodological support approaches needed to tackle the challenges of uncertain and complex requirements, amorphous procedures and increasing systems complexity in early stage naval vessels design by a MDM-based research approach. For this purpose the activities of SDS, SE Vee Model and agile method Scrum as well as an Agile Systems Architectural Pattern on MCS level were mapped in an MDM. By analyzing inter-product-process-dependencies for naval vessels and intra-process-dependencies of the activities of the introduced methodological support approaches, an integrated approach for concept design is proposed. As the possible degree of agility in the development system (process) and in the system to be developed (product) depend on each other, the transmission of an Agile Systems Architectural Pattern for naval vessels concept design on MCS level is proposed as well. The suggested integration of the several methodological support approaches is supposed to enhance the ability to tackle current and future challenges in naval vessels early stage design.

As the presented results relay on theoretical considerations, the practical implementation and result monitoring of the proposed approach gives several opportunities for follow on research. The extraction and analysis of empirical data to validate the presumed dependencies presented in the MDM is a necessary step for follow on research. Classical DSM applications for analysis and optimization as proposed by Eppinger (2012) could give additional impulses for processual and architectural improvement. The extension of the MDM mapping for integration of further methodological support to naval vessels design gives additional follow-on research opportunities. Especially the integration of scaled agile methods to naval ship design will be a necessary step for practical implementation during design phases of preliminary design and detailed design. A combination with the SAFe MDM optimization approach by Narayanan et al. (2021) seems suitable. The extension of the MDM by an organization architecture DSM will give additional insights. Overall MDM based research approaches seem to offer great opportunities to transfer and integrate general methodological support approaches to special domain of naval ship design.

Since other industries also face complex challenges that cannot be addressed by a single methodological support approach and need consideration of process and product dependencies, the transmission of the presented MDM based research approach for prescription and integration of other industry-specific process architectures and product architectures is a further research opportunity.

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