A different view on system decomposition – subsystem-centered property evaluation in multiple supersystems

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Abstract This paper motivates the need for enhanced support for subsystem development and evaluation in the context of large engineering systems. Established approaches e.g. from the field of systems engineering seem to provide too little differentiation between how system development ideally should be approached and what "channels" (means) are realistically available for a company developing these systems. The research presented is motivated by the challenges identified in the context of the offshore petroleum drilling industry and the assumption that the challenges system providers face in that context are representative for other industries as well.

We propose a framework for addressing these challenges, aiming at supporting the evaluation basis for a subsystem by its projection into multiple supersystems and stakeholder systems. We specify the requirements differentiating different possible strategic and operational directions. We confront the identified requirements and potential directions to specific research areas, and established methods and tools, usually being applied in the context of overall system development or described only generally. We investigate which sub-aspects of the envisaged framework are being implicitly or explicitly addressed by these approaches and estimate their transferability potential. The identified potentials and limitations of the different approaches constitute the basis for a further substantiation of the framework.

1 Introduction

One of the main goals of system development can be narrowed down to the challenges of identifying which properties are considered valuable by the stakeholders and finding a solution to consistently incorporate these properties into a system. It is self-evident, that the difficulty of achieving that goal is closely related to the complexity of the system to design. Another domain largely determinative for the specific challenges of that task is the "value creating network" (VCN) comprising the stakeholders involved in creating and maintaining the system and/or delivering their services using the system or parts of it. Furthermore, the VCN determines the ways in which stakeholders are contractually interrelated and the established mechanisms existing in particular industries constitute important boundary conditions for system development.

Moreover, it constitutes the basis for the interests and preferences of the involved stakeholders.

There are different overall approaches supporting the structured and organized development of complex systems as well as specific methods and tools supporting particular tasks or perspectives. Two of the most established overall approaches are systematic design [1, 2] and systems engineering [3, 4], both inheriting systems thinking as a very central aspect. While systematic design focuses on certain core principles and emphasizes a systematic approach to problem solving, systems engineering aims at an integrated consideration of the technical, social, and business aspects of a system. It constitutes a holistic, hierarchical decomposition approach to the design process, incorporating subsystem interactions, emergent functional behaviors and system integration [5]. As an iterative process of top-down synthesis it is considered to "enable the realization of successful systems" in a "near optimal manner" [3].

Nonetheless, these established approaches seem to provide too little differentiation between how system development ideally should be approached and what "channels" (means) are realistically available for a company developing these systems. The research presented is motivated by the challenges identified in the context of the offshore drilling industry and the assumption that the challenges system providers face in that context apply similarly for other industries.

Historically grown and established business structures and mechanisms within the VCN of certain industries can constitute obstacles to system providers to directly apply the principles of hierarchical decomposition and top-down synthesis on an overall system level. Different drivers have contributed to the fact that systems have grown somehow evolutionary and are still developed by reusing proven designs, explicitly accepting not to know how far away these systems' properties are from a possible optimum. Examples for these drivers are conservatism and high investments on the one hand and complex and extremely time-critical tendering and bidding processes during system acquisition and specification on the other hand as shown in [6].

However, a fundamental part of the basis for overall system development is the portfolio of subsystems available within a company at that point in time, constituting more or less distributed modules when integrated in an overall system. In certain industries developing and deploying large-scale industrial systems, the development of these modules run decoupled from overall system level design. The term "design channel" is introduced in order to emphasize that considering design on different levels has to include the corresponding development phases and cycles as well as the respective development conditions. While subsystem development aims at customer neutrally updating or enhancing a company's portfolio, overall system level design is essentially customer driven and thereby governed by tendering processes and other business related mechanisms. Subsystem development consequently must be considered by system providers as the only "design channel" providing realistic conditions for a sound (methodic) consideration and evaluation of the subsystems' properties and its contribution to the various supersystems' properties and their behavior (the term supersystem is very important in this paper and used – analogous to "subsystem" – referring to levels higher in the system hierarchy; the overall system is a supersystem for each subsystem, but also elements on intermediate levels constitute supersystems for elements on lower levels).

Nonetheless, the perspective of subsystem development seems considerably underrepresented in the established approaches, handling subsystem development as an integrated part of system development rather than as a discipline with very specific challenges and potentials and a completely differing starting point and problems to solve.

Method and structure

In order to further clarify the outlined challenges, in the next chapter we summarize the situation acquired in an in-depth case study from the offshore drilling industry based on industrial publications (e.g. [7-9]) as well as on several workshops with a system provider (including experts from management and business development but also experts with operational experience) and additional semi-structured interviews with experts from further core stakeholders of the VCN: two with an oil company (operator) and one each with experts from a main drilling contractor and a ship yard. We illustrate the importance for the system supplier to enhance systems thinking especially during subsystem development, and thereby to exploit this design channel more consciously. Our core interest is directed to the multi-faceted domain of properties on different hierarchical levels of the system, the role of property types, the question of dependencies and aggregation as well as the subjective interest or "value" related to properties from different stakeholders' perspectives. Focusing on subsystem development as the selected design channel, the dependencies between properties have to be considered not only in one specific supersystem but in different relevant supersystems. The differentiation of supersystems has to apply on the one hand within one overall system (e.g. different subsets of subsystems, contributing to certain technical main processes), on the other hand as a differentiation of overall systems (as supersystems) themselves. Additionally, variations in the stakeholder network can result in different possible sets of stakeholder interests related to these properties.

In the third chapter we propose a framework integrating these requirements, aiming at supporting the evaluation basis for a subsystem by its projection into multiple supersystems and stakeholder systems. We confront the identified framework elements to specific research areas, and established methods and tools, usually applied in the context of overall system development or in a non-specified context. We investigate which sub-aspects of the envisaged framework are being implicitly or explicitly addressed by these approaches and estimate their transferability potential. The identified potentials and limitations of the different approaches constitute the basis for a further substantiation of the framework.

2 In-depth case study for systematic clarification of the problem

In the value creating networks (VCN) of the offshore drilling industry, numerous stakeholders with very different expertise and economic power contribute with their systems and services to the achievement of the overall objective of drilling a well in order to detect oil or gas reservoirs, create access to them and assure exploitability completing the well with the required installations. The large-scale complex drilling systems deployed for these purposes from the water surface have to enable very different operational processes (OP) under the water and in the formation under the seabed such as drilling, measuring, pressure control or stabilizing the borehole by cementing casings into it.

The hierarchy within drilling systems

The drilling systems consist of numerous interacting subsystems (some of which can be seen as modules) arranged on and integrated into the hull of a floating platform or ship. Different subsets ("operational process systems" – OPS) of interacting subsystems are needed for different OPs, to a large extent linked to the transport and mounting/dismounting of very different functional elements (e.g. drill bits, drill pipes, measuring equipment, huge valves, etc.) needed in the borehole as well as their electronic, mechanical or hydraulic actuation. The OPSs for the different OPs are not independent and decoupled but highly overlapping. Rigging and adapting subsystems when changing from one OP to another is often necessary. The use of a subsystem for different OPs leads to reduced space and weight consumption, being a crucial issue for these systems, as well as to potential investment reductions. On the other hand this limits the possibilities of concurrent execution of OPs, and increases the importance of reliability and durability. Optimal system performance is thus depending on properties across all hierarchy levels from the overall system architecture, over the OPSs to the subsystems. Nonetheless, in reality, these levels are addressed over different design channels, and not in an integral, top-down system synthesis process.

In this sense, similarities to the field of systems of systems (SoS) exist. On the other hand some of the key characteristics of SoS do not apply to the described class of systems such as operational independence (subsystems achieve well substantiated purposes even if detached from the SoS), managerial independence (subsystems are developed and managed for their own purposes).

Stakeholder roles, constellations and perspectives

The result of successful system development is the embodiment of the set of properties that bears the most value. Besides the technical challenge of incorporating these properties into a system, the question of the most valuable set of properties will lead to different answers depending on the stakeholder. Per definition, in business environments, the stakeholders' major interest into the properties of a system is how they affect the profitability (long-term or short-term, depending on their strategy) of their business (which doesn't mean that they have a clear judgment on the effects).

In the drilling industry, a high number of stakeholders contribute to overall value creation. Major stakeholders and their typical tasks are

- (SP) the system provider: responsible for designing and manufacturing the drilling system

- (OP) the drilling operator (oil company): possessing the rights to drill and exploit the resources in a defined area
- (DC) the main drilling contractor, being engaged by the operator for the execution of the drilling services – main user of the drilling system
- (SY) the shipyard, constructing the hull and integrating the drilling system
- several other stakeholders such as the hull designer, suppliers of subsystems, special equipment or consumables, sub-contractors for special services, etc.

According to the stakeholders' roles and their interfaces to the system, different properties are relevant for them. Their priorities and preferences regarding these properties' values are often conflicting as also stated in [10]. The stakeholders form a value creating network (VCN) whose structure results from the existence of business relationships amongst each other. But not only the structure of the stakeholder system (fig. 1, right) is relevant, also the specific relation type, meaning the agreed obligations (constituting cost and risk) and remuneration principles.

For the system provider it is essential, if the drilling contractor (DC), the operator (OP) or the shipyard (SY) is his direct customer, which refers to the structural dimension. Possible value related properties relevant for these stakeholders can be high reliability and availability (for DC), high time efficiency (for OP), or low equipment and engineering cost (for SY). But for the DC, time efficiency can gain relative importance compared to reliability if incentives are integrated in the remuneration such as being rewarded by meters drilled per day instead of fixed day rates – this refers to the dimension of relation type. Both dimensions together are referred to as the "stakeholder constellation".

Incremental development and design channels

A lot of systems deployed in the drilling industry are far away from providing an optimal behavior, which on the one hand has to do with a high uncertainty in various domains over the lifecycle of a drilling system, e.g. related to changing operational contexts or market aspects as elaborated upon in [6]. On the other hand, we identified several industry inherent triggers (simplified):

- Due to strict safety requirements, sticking widely to proven system designs with medium performance finds more acceptance than aiming at radical improvements with higher risk and certification effort.
- High investment costs for the development of completely new concepts.
- Based on fast growing requirements with respect to higher safety, higher water and drilling depths, wider functional scope and areas with more extreme natural conditions (e.g. drilling in the arctic), efforts have been concentrated on extending established system designs' absolute capabilities, which did not provide the room for holistically re-thinking the overall system.
- A growing variety of system designs due to more radical changes would constitute less flexibility regarding the allocation of operating and maintenance staff (respectively higher training efforts)
- The resulting evolutionary, incremental development of the overall system designs is also mirrored on subsystem level, where clear modules for certain functions have

evolved over time. Making radical changes on the system level would also necessitate breaking up some of these established modules, which would again be very costly and enhance the proneness of failure.

- Usually, an overall system design is being proposed as a reaction to a call for tender. The fact that the system provider usually has to bid within a very short period of time makes it virtually impossible to come up with a solution resulting from a systematic decomposition of the design problem. Consequently, the one existing solution being closest to the required specifications is selected and adapted. Often customers even specify their demands explicitly referring to an existing design.

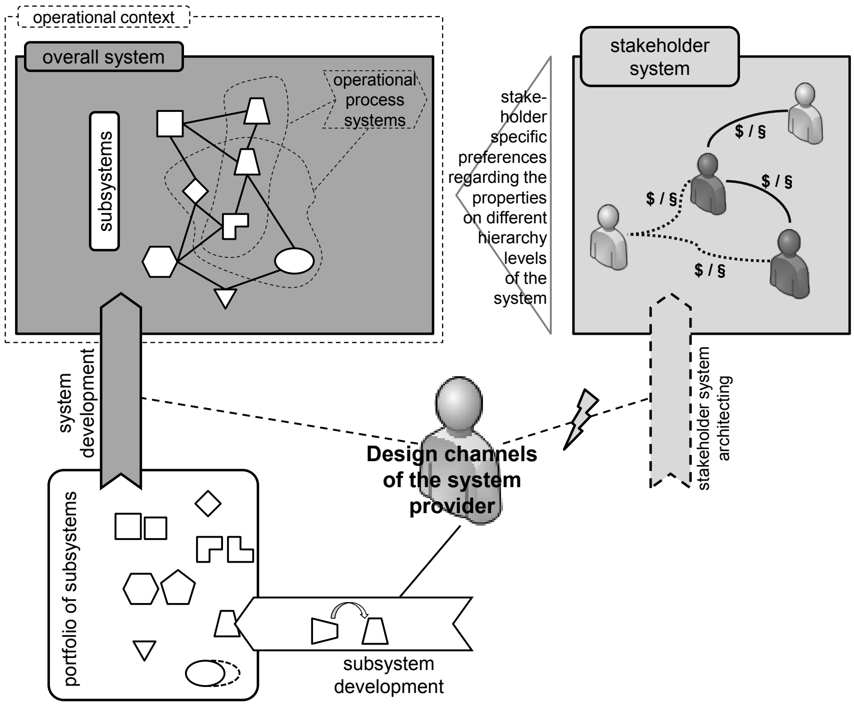

Fig. 1 Different hierarchy levels of a drilling system and related design channels of the system provider (left). Stakeholder system with established roles and constellations – determinative for property preferences but no possibility for the system provider to take influence (right).

Even for ambitious and innovation oriented system providers these factors constitute essential obstacles for challenging established designs and approach new concepts holistically, thus over the design channel of system development. Under these circumstances the strategic meaning of the design channel of subsystem development has to be emphasized. Not only can subsystem development be driven based on internal business cases independently from customer tendering processes. Also, forming the (incrementally developed) portfolio and thereby the building blocks of the future overall systems, the (incrementally developed) subsystems constitute the actual drivers of future system designs and not vice versa as proposed as ideal approach by systems engineering.

Nonetheless, in our case study we observed a lack of systems thinking in the context of subsystem development. This has been derived from the analysis of different examples of recent subsystem developments and their acceptance on the market. Generalized, problem solving has been too much focused on the main technical objectives, having been achieved very successfully. At the same time, often developments were below expectations as important side effects in other domains have not been identified. Examples are:

- Focusing on the preferences of one stakeholder (even though he is the initiator of a development project) without evaluating a development's resulting property set from the perspectives of other stakeholders can retaliate if those are potential customers of overall systems as well.
- Limiting verification to properties on the subsystem level without estimating their (emergent) effects on higher hierarchy levels.
- Limiting considerations on higher hierarchy levels to single supersystems:
    - The relative importance of a subsystem's reliability depends on the question if the supersystem provides redundancy for its function.
    - Eliminate weaknesses for one OPS can imply essential new weaknesses for another

In the next chapter we specify the need for approaches supporting systems thinking explicitly in the context of subsystem development and evaluation and propose a conceptual framework derived from these needs.

3 The needs for a multi-supersystem evaluation framework

As we have shown, certain industries entail boundary conditions that constitute obstacles for systematic development on the overall system level, so that the design channel of subsystem development gains importance in order to systematically introduce improvements and guarantee competitiveness. Nonetheless, introducing changes on the subsystem level, it becomes all the more critical to consider that the effects space of a subsystem design is larger than the design space itself, and the supersystems are of multiple nature.

Numerous authors emphasize the importance of early validation and verification [3, 11] and pinpoint at the risk of high market losses due to launching decisions without appropriate evaluation activities [12]. With the framework proposed in the following and its further development we want to contribute to this field especially with respect to an enhancement of transparency of the different effects the changed properties of a subsystem can have on other hierarchy levels, in the context of multiple possible supersystems and under consideration of varying sets of stakeholder preferences.

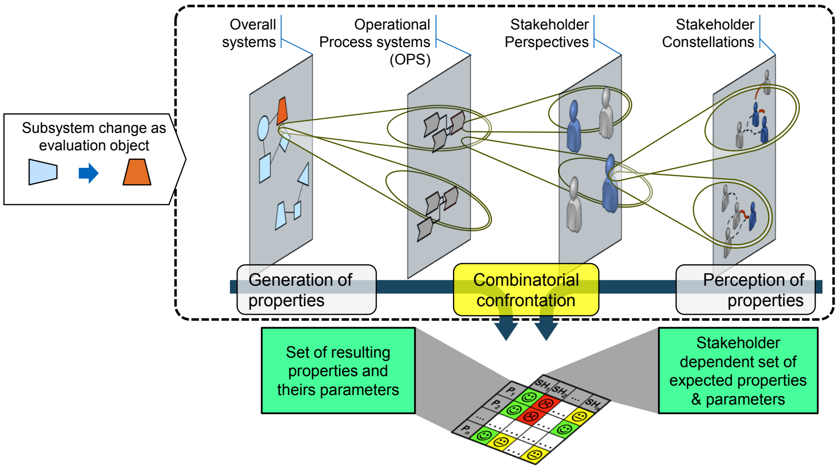

Fig. 2. Basic structure of the framework

As shown in fig. 2, the bottom-line of the framework is the confrontation of the two sides of the "objective" generation of properties through the chosen subsystem design (represented as a change from a former design) and the "subjective" perception of these properties by the stakeholders. The first level of the evaluation problem is based on a selected overall system and a selected stakeholder constellation, the subsystem is projected into. The layer of OPS (see also fig. 1) enables a systematized inquiry of the subsystem's properties' effects in the context of the different operational processes it contributes to.

In order to address the evaluation problem holistically, appropriate variations have to be made in the layers of the supersystems (overall systems as well as OPSs within each overall system) as well as the stakeholder constellations, resulting in a set of confrontation results based on their combinatorics.

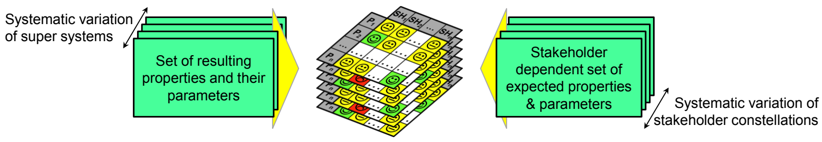

Fig. 3 Combinatorial confrontation

The framework aims at enhancing the transparency regarding the overall picture of confrontation results as well as at supporting the identification of otherwise neglected discrepancies. It shall thereby substantiate the basis for assessment and decision making where the results have to be interpreted based on defined strategies. But which aspects of related approaches and methods can be picked up in order to substantiate this framework? Are their basic ideas compatible and transferable to a subsystem-centered approach? The next chapter discusses some of them with respect to their potential to support possible directions of further development of the framework.

4 Potential and limitations of related approaches

Stakeholder value perspectives and stakeholder networks

There are different concepts of linking system or engineering parameters to subjective stakeholder preferences such as QFD [13] (see below) or value measurement using key parameters (KPs) [14, 15]. The latter provides a quantification method based on stakeholder specific subsets of weighted KPs and the derivation of a total value weighting stakeholders by relative importance. The approach also covers the KPs evolution over time (e.g. due to changing preferences or new technologies) which should be considered as an important perspective for our framework as well. Nonetheless, the interdependencies between the KPs respectively the questions which KPs can be actively influenced are not addressed.

In the area of stakeholder networks many approaches focus on high level systems architecting [16, 17] including the architecture of the stakeholder network itself. From the point of view of a drilling system provider, the stakeholder system has to be dealt with as a boundary condition as no influence on it is given (see fig. 1). Nonetheless, as shown above constellation variations have a high influence on the perception side of the framework, and modeling tangible and intangible value flows [16] can help deriving stakeholder preferences of the system's properties.

Property-based approaches and dependencies between different types and hierarchy levels

The dependencies between attributes directly designable and measurable and attributes resulting from their aggregation (the latter usually being those of interest for the customers and other stakeholders) are the core of many theories and approaches supporting different objectives. Examples are CPM/PDD [18], differentiating between characteristics and properties, or axiomatic design [19], where design parameters are translated into functional parameters. A more detailed differentiation based on the aggregation mechanisms to higher levels in the decomposition is provided in [5], listing (in order of increasing complexity) attributes which aggregate (1) depending on system composition (e.g. mass), (2) system structure (e.g. cost), system operation (e.g. reliability) or (4) resulting from complex emergent behavior (e.g. passenger wait times for a train system).

The house of quality (HoQ) – a largely established visual support developed in the context of the method QFD [13] – allows to allocate engineering characteristics (EC) to customer attributes (CA) as well as to qualitatively represent their direct relations to other engineering characteristics. This supports the reflection on direct and simple indirect consequences of changes of ECs for the CA. Nonetheless, complex aggregation mechanisms cannot be covered by that approach. The fact that the customer speaks with a "common voice" also does not allow for the consideration of conflicting interests – covered conflicts are thereby limited to system inherent "technical" conflicts. Furthermore, the variation of supersystems or interfaced subsystems is not supported.

Lifecycle properties also referred to as "ilities" (e.g. maintainability, safety) constitute another essential group properties "that often manifest themselves after a system has been put to initial use. [...] they do not include factors that are always present, including size and weight" [20]. DfX-guidelines are valuable sources to identify links between parameters on lower levels and lifecycle properties [21].

5 Discussion

Subsystems driven design in a way conflicts with system engineering's main principles of top-down synthesis where subsystems result from an explicit decomposition process, and decisions on system and subsystem level can be reflected in both directions, based on the increasingly precise estimation of the resulting properties and their aggregation [5]. Nonetheless – as shown in our case study – in certain industries the design channel of subsystem development provides more potential for systematic development than the design channel of overall system design.

Therefore, the presented framework aims explicitly at supporting the design channel of subsystem development, especially trying to respond to the differing challenges with respect to the resulting evaluation problems. On the one hand, the system of interest [3] (and thus the object of evaluation) becomes smaller in scope meaning also a reduced number of variable parameters in contrast to a holistically designed system. At the same time, the effects space (the overall system) has to be considered in multiple relevant variations in order to reduce the risk of critical discrepancies in the form of the number or severity of mismatches between (sub)system properties and stakeholder preferences.

The framework provides a wide range of potentials from the evaluation of a subsystem design concept to the analysis of existing subsystems in order to derive development goals. Besides, it enhances the understanding of the own systems and their properties, e.g. addressing the question which mechanisms can be found that explain why a property gains or loses importance? Fig. 4 outlines exemplary possible analysis objectives:

- Analysis objective 1 – How does the overall picture of the perceived value that results from a subsystem change in a given overall system change as a function of the underlying stakeholder constellations?
- Analysis objective 2 – How does the perceived value of a specific stakeholder resulting from a subsystem change in a given overall system change as a function of the underlying stakeholder constellations?
- Analysis objective 3 – How does the perceived value of a specific stakeholder in a given stakeholder constellation change depending on the type of overall system a changed subsystem is integrated in? And how can be known which aspects of that variation can be related to the subsystem?

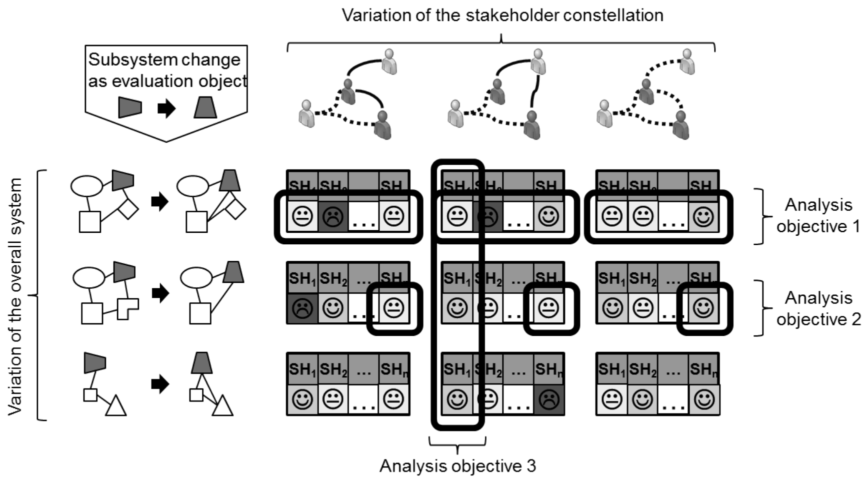

Fig. 4 Exemplary analysis objectives supported by the framework

In all of these cases, average values, variances and outliers might be of relevance, depending on the decision to take.

6 Outlook

For the moment, the framework aims at contributing to the field of approaches supporting the organization of information. It integrates ideas from related approaches such as CPM/PDD [18] or QFD [13], and enhancing these approaches towards some of the identified missing aspects seems feasible such as representing the effects of varying supersystems or the differentiation of stakeholder perspectives.

On the other hand important questions remain unmentioned or unanswered by these approaches, e.g. how can be assured, that all relevant properties have been considered? Although CPM/PDD provides for the integration of “additional properties” [18] – properties that haven’t been originally considered and are identified in the course of the design process – their identification is not supported systematically. Also in simulation approaches applied to estimate the aggregation effects of properties, the considered parameters need to be predefined [5].

Another topic to be addressed in future research is the question of how to support the selection of supersystems for the scenario building and how to integrate the anticipation of future changes on system level. A differentiation between the subsystems’ integration in new systems and the replacement in upgraded systems also has to be investigated with respect to effects on the framework’s requirements.

At this time, we have not completed a detailed application case of these ideas. Nonetheless, we view this framework as a platform for research rather than a finished product. It has many interfaces to related approaches and combines the challenges of different other related problems, some of which are not satisfactorily solved and to which this research intends to contribute.

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