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Modellability of System Characteristics - Using Formal Mark-up Languages for Change Capability by Design

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Abstract

Change capability enables a production system to cope with external influences in an efficient, fast and self-organized manner. Several approaches have been designed for measuring change capability by specific indicators which represent core characteristics of production systems. On the other hand, formal modelling languages are used for production system design. Unfortunately, these languages do not match with system characteristics and especially with those indicators of change capability. Due to this missing linkage, existent production system models don't facilitate the implementation of a system´s change capability by design. Goal of this contribution is to point out the possibilities of operationalization approaches and their potential to be extended for (formal) modelling of system characteristics and sub properties, exemplified by using the concept of change capability. Additionally, the potential of change capability to be representable in a formal language will be exemplarily outlined by emphasizing on Systems Modelling Language (SysML). For this purpose, a qualitative approach with an emphasis on literature- and content analysis will be applied. Results of this contribution are (1) to pinpoint the research gap (which is also of crucial practical relevance) and (2) to point out possible solution approaches for a formal modellability of system characteristics.

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1. Introduction

The capability to conform with environmental turbulences in a fast, efficient and autonomous manner [1,2] is necessary for an organisations survivability in steady changing business environments such as in current times. This system capability is summarized under the concept of change capability (“changeablity“ [3], “agility“ [4], “strategic flexibility“ [5], “evolvability“ [6]). Needless to mention that this capability has to be operationalized and measurable for an organisations context sensitive modification and design. In this context, operationalization refers to the operations by which an object of observation is measured [7]; especially to correspondence rules which links intangible phenomena with directly experienceable and measurable facts. A system operationalization enables an engineer to scrutiny the alignment of requirements and the characteristics of a real system. However, it does not enable an engineer to use these requirements for the design and implementation of a real system. For the purpose of system design, the engineer needs specification- and modelling techniques.

The simulation of system behaviour enables system designers and engineers to consider different architectural alternatives with relatively little effort and prior to real implementations. Hence, modellability and formalisation of system characteristics constitute substantial requirements for system design. Formal models are reality representations formulated in formal languages, which consist of a defined set of symbols, formation rules, transformation rules, and axioms. Adding to the completely specified language syntax an unequivocal interpretation leads to the semantics of the formal model and its meta-model. Consequently, formal change capability models would allow operations for combination and alteration of system capabilities, including such effects as emergence and submergence. On the other hand, formal models could design a (or more than one) target system of

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change capability (or other capabilities) by connecting existing capabilities or properties with each other. Additionally, they would allow an automated *ex ante* analysis and the processing of design alternatives if the system characteristics are formulated in a computer processable form. To summarise generally, formalised models aid to understand the interaction of system components and -functions and enable an automated transfer in simulatable models.

Existing change capability approaches are mostly operationalized [3,8,9,10,11,12]. However, they don‘t provide any kind of formal modelling. This is sufficient for behavioural science research. However the next step, the engineering formal modelling which enables the generation of transferable models for product or system development is still missing. Accordingly, manual model transformation (for instance a manual comparison with requirements) is still necessary, yet laboriously and not contemporarily.

Goal of this contribution is to point out the possibilities of operationalization approaches and their potential to be extended for formal modelling of system characteristics and sub properties, exemplified by using the concept of change capability. Additionally, the potential of change capability to be representable in a formal language will be exemplarily outlined by emphasising on SysML. For this purpose, a qualitative approach with an emphasis on literature- and content analysis will be applied. Results of this contribution are (1) to pinpoint the gap in research and (2) to point out possible solution approaches for a formal modellability of system characteristics.

The paper is organised as follows: Section 2 explicates an understanding of the term change capability. Section 3 comprises a consideration and discussion of different change capability approaches against the background of formal modelling, while Section 4 presents possible solution approaches for strict formal modelling of change capability. Section 5 emphasises on modelling change capability with SysML and the conclusions are exemplified in Section 6.

2. Change Capability – Concept Comprehension

There are various terms that deal with the concept and understanding of change capability - which are synonymously used in this paper - such as adaptability, agility, changeability, evolvability, or strategic flexibility. Reasons for this term diversity are different application contexts and perspectives of consideration.

Change capability is a compound term. Thereby change is understood as an objects transition from a current status in n to a different status in $n+1$ [9], which is a continuous developing process with an infinite number of transition states. Capability refers to a systems power to perform an action. Whereby socio-technical systems are able to learn (ability) and are characterised by system inherent powers to perform an action (capacity). Capability comprises both, the system inherent as well as the learnable components.

Change is induced by turbulences. These turbulences are the effect extent of complexity and dynamic in business environments [13] and - if they affect an organisation - create change driver, which may lead to need for change. Turbulences occur in a system if the environmental requirements exceed the organisations inherent capabilities and competencies to cope with these requirements. The stronger these turbulences and change driver are, the higher is the need for handling these changes. Besides an ability for carrying activities out ("can"), employees willingness ("want") as well as the eligibility by organizational framework conditions ("allowed") are necessary for coping with the need for change ("must") by executing an action (“do”). A balanced ratio of these factors testifies change capability. Consequently, in context of organizational change, besides the capability to cope with a change (change capability), facilitating organizational framework conditions in terms of change enabler and staff readiness (willingness to change) to handle the change, have to be present for achieving change success (cf. Fig. 1) [1].

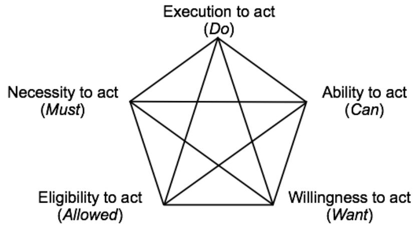

Fig. 1. Change modalities.

Changeability comprises proactive and reactive components. Following this, Meier et al. [10] refer to the definition of Hernandez [14] who defines changeability as a factories potential to carry out target-oriented new- and re-configurations in a reactive or proactive way. Change drivers such as demand volatility or new technological developments trigger the impulse for a change. Wiendahl et al. define changeability as “characteristics to accomplish early and foresighted adjustments of the factory‘s structures and processes on all levels to change impulses economically“ [3]. Nyhuis clusters changeability into technical, spatial, and organizational changeability [15]. They identify five change enabler which provide the ability to adapt to these environmental changes: compatibility, mobility, modularity, scalability, and universality [3].

According to Borches/Bonnema evolvability characterises the ability to adapt to changing environments time- and cost-efficiently [16]. This adaption will be executed at lower-costs than a system new development [6].

Strategic flexibility enables an organisation to react towards diverse requirements of dynamic competitive environments [17] and purposefully modify strategic elements such as structure, strategy, resources, and competencies [18]. This enables the generation of competitive advantages by developing alternative paths of action or strategic options.

Sambamurthy uses the term of agility for describing the capability to detect innovation potentials and use market opportunities by the fastly and efficiently combination and usage of resources, knowledge, and relationships [19]. Operational-, partner-, and customer agility are distinguishable components, which are triggered by intensive market rivalry, globalisation as well as pressure due to shorter product launch times [4].

Change capability enables organizations to efficiently and effectively conform to environmental turbulences. Conform, thereby, comprises the combination of proactive, inactive, passive, and reactive activity types. It enables a system (technical, social, or socio-technical as organizations) to perceive and handle impacts from its environment in a fast, efficient and autonomous manner [1,2]. Relevant aspects are proactivity, efficiency, and perception of the environment. Systems will be enabled to capture relevant environmental influences, analyse the internal and external situation, identify and assess risks, develop alternatives of action, choose the context-sensitive fittest alternative in regards to system goals and framework conditions, and to act purposefully in its relevant environment. This comprises the set of system inherent capabilities for coping with external and internal effects, generate proactively change patterns as well as derive courses of actions from them, and passively solely resist situations and influences.

Normally, change capability definitions are developed in dependence from a specific application context. Change capability is not directly measureable. Hence, an additional step of refinement from characteristics by definition to auxiliary characteristics of the operationalization is necessary. In this way, different change capability definitions can coexist. However, it is mandatory that these definitions base on the same operationalization approach. Thus, for requirements derivation of specification languages for modelling change capability it is valid that, on the one hand, the specification languages are independent from a specific definition and, on the other hand, that they are sufficient for every definition. Yet, the introduction of different definitions was necessary for creating a mutual understanding of change capability.

3. Operationalization Approaches of Change Capability

An operationalization on the basis of definitional indicators presupposes an intentional definition of the change capability concept. Within the concept of definitional indicators those system characteristics will be measured, which are direct elements of a change capability definition. Each definition (cf. Sec. 2) is a suitable basis for a definitional indication. For instance, a system can be investigated regarding its velocity, autonomy, and efficiency of dealing with environmental changes [20]. This type of operationalization relies on specific phenomena of changeable systems, which an author considers as relevant in his research context.

Correlating indicators are based on system characteristics. These are such system characteristics, which foster the values of definitional characteristics. Furthermore, these indicators may enable a differentiated consideration of a system. Such approaches are nevertheless independent from a concrete definition of change capability. A specific difficulty in this context is the meaningful and redundancy-free arrangement of indicators.

Deductive indicators use characteristics, which are not directly related to the concept of change capability. This can be done by means of aggregated and connected operating figures such as: number of process changes, utilization before and after a process changes, or number and regularity of external effects. Those figures can be used and grouped as key figures for developing, implementing, and measuring diverse change capability strategies [11].

Those three previously mentioned operationalization types can be reflected as static approaches. They consider and evaluate a system independently from specific environmental effects. Thereby, they although can be used for the proactive design of a changeable system, however, they cannot ensure that the available change capability is appropriate (too much or too little) for relevant or probable environmental effects. Thus, dynamic approaches which consider change capability by means of specific environment- and system situations evolved.

A dynamic and definitional approach is the equilibration [21,22]. This principle has its origin in biology and general system theory. The core idea is that systems continuously work on the disintegration of inner stress states. Change capability will then be assumed, if necessity of action, ability to act, willingness to act, eligibility to act, and execution to act (measured by means of the consequences of action) are in an equilibrium towards each other so that no aspect dominates the others or is dominated by another [11].

Change capability can be evaluated correlatively by consideration of the available room for manoeuvre in a specific situation. The more patterns of action are available in case of an external effect and the more feasible these patterns are, the more is a system capable of changes [23,24].

A deductive and dynamic operationalization approach can take place by simulation. For instance, impacts of disturbances on a system can be simulated. By means of changes of a systems‘ performance capacity derivations regarding the systems change capability can be concluded [11]. The indirect measurement takes place by means of classical operating figures. Cause-effect relationships towards the actual change capability, however, have to be verified by means of quantitative methods.

In context of resilience research, approaches exist which emphasize on system characteristics as robustness and stability. The underlying idea is that a system is more able to ward off and cope with occurring environmental influences by means of maximize those characteristics [25,26,27]. The focus lies on maintaining an existing system state. Hence, the primary design intention is rather a reactive reorganization of the system itself than to enable proactive influences on the environment. Conceivable approaches are interdependency analyses [28,29,30].

The analysis of environmental turbulences represents another approach to operationalize change capability. While interdependencies are related to individual influences towards a system, the turbulence-based approach aims to identify the spectrum of diverse possible kinds of influences. Goal of this approach is to develop and maintain an appropriate perception of the environment, which enables the system to proactive recommendations of action for the internal system design.

4. Solution Approaches for a Formalized Modeling of Change Capability

The transfer of the specific change capability aspects into requirements concerning a modelling language takes place via the common system theoretical denominator. Both, change capability and system modelling have to consider architecture (static) as well as behaviour (dynamic) of system structures. Additionally, perception of the environment and the focus towards the system goals are further necessary parameter (cf. Fig. 2).

Every system consists of elements which constitute the basis for establishing structures and relations. This enables the definition of an appropriate system boundary. A system boundary implicitly determines which external influences exist and which have to be captured by the system sensors. This constitutes the basis for the consciousness as well as the self- and environmental perception of a system, which enables an independent acting. Furthermore, the range of available patterns of action constitutes a systems' capacities and abilities. These will be applied for achieving the system goals.

The concept of modality is applicable for further differentiation of the aforementioned system aspects [11]. Modality is specified as the kind and manner, the possibility, or the condition under which something arises or exists (ontological modality), or is claimed (logical modality) [31]. The ontological modality expresses whether something is necessary or possible. This concept can be used for emphasizing on development stages of the mind and thinking as well as objects and processes [31].

Elements, relations and system borders constitute the framework conditions (be allowed). Environmental sensors recognize external constraints and the necessity to act (must). Consciousness and perception create the willingness to act (want), while acting represents the real behaviour (do), and capacities and abilities describe the effective ability to act (can). There exist no hierarchy between these modalities. Thus, if the value attributes of these modalities are in equilibrium then the system goals are achievable without any frictional loss.

The operationalization approaches of change capability rely on diverse system perspectives. A change capability evaluation based on operative figures is conducted by the analysis of system elements using deductive indicators (see [11]). Static system architectures will be evaluated with the aid of system relations. For this purpose, correlating indicators can be applied [14]. When considering the system resistance towards external influences (passive change capability by robustness and stability), the system boarder is the focal aspect. Another type of passive change capability is the purposeful perception of the environment and within this the internal-reactive redesign of system structures. Additionally, the perceptual capacity is also the basis for an active change capability. A decisive characteristic of a systems active change capability is the proactive design of the environmental conditions. The available freedom of design is determined by its available patterns of action in a specific situation. The more and the more promising patterns are available, the higher is the systems degree of change capability [12,23]. On the level of capacities and abilities, change capability can be operationalized by its constituting characteristics in form of definitional indicators. Thereby, with a focus on system goals an optimal degree of change capability can be verified, if all system goals are actually met.

The change capability operationalization occurs in all the aforementioned perspectives necessarily via indicators. However, the retrospective analysis is not suitable for an anticipatory design of changeable systems (Change Capability

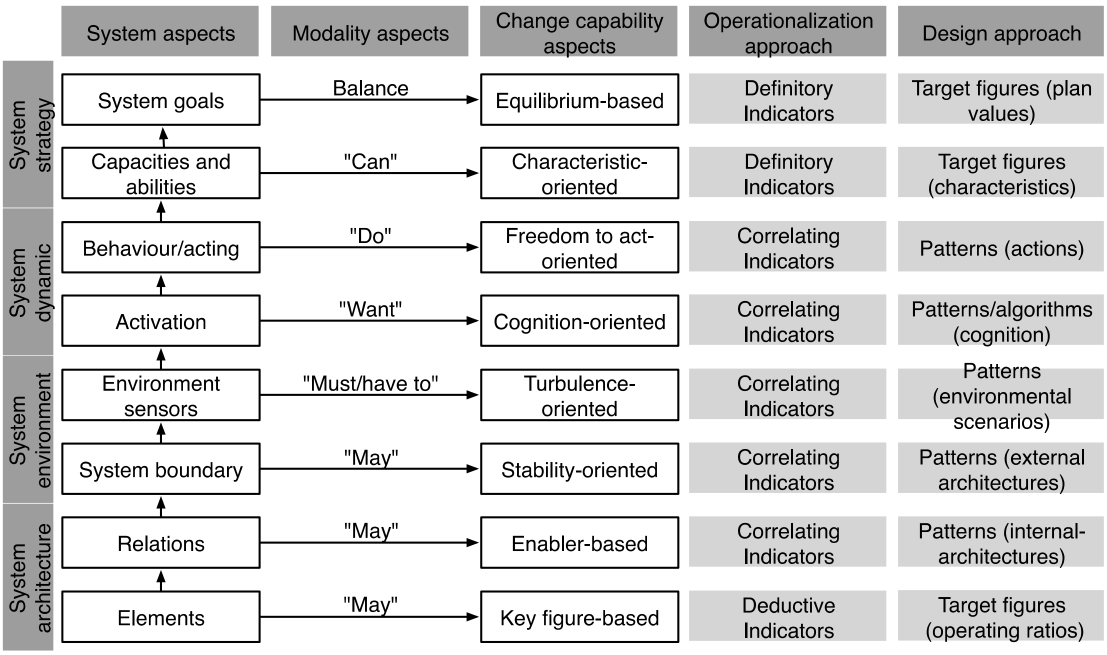

Fig. 2. Operationalization and design approaches for change capability.

by Design). In this context, the usage of to be optimized target figures and pre-defined design patterns is appropriate and promising. Which target figures and which kind of patterns are relevant can be derived from the system aspect hierarchy of change capability.

The characteristics of individual system elements can be aggregated into key indicator systems, which describe the fulfilment level of a specific system alignment (e.g. maximization of the room for manoeuvre, minimization of turbulences, minimization of change time etc.). Changeable relations or structures are designed by the usage of approved architectural patterns. The same applies to structures and relations of a systems stability and robustness. The requirements concerning the system sensors are derived from possible environmental scenarios (patterns). Therefore necessary perception and processing of system- and environment information require calculation capacity and the presence of cognitive patterns. The necessary room for manoeuvre for pre-defined scenarios can be specified by the aid of patterns of action. Hence, constitutional characteristics of change capability can be used as to be optimized target figures. The same applies for system goals.

Specific target figures and –patterns are necessary for the concrete system design. Present research provides these figures and patterns. Examples for change enabler as correlating indicators for changeable system structures are scalability, modularity, redundancy, interoperability, or self-organisation [1,3, 10, 16, 20]. Examples for generic patterns of action, which determine the room for manoeuvre as correlating indicators are mobility, abrasivity, separation, suggestion, elasticity, or recombination [2]. The availability of these patterns or target figures is not a requirement towards modelling languages, but rather the ability to specify such patterns and target figures is.

5. Possibilities of Using SysML for Modeling

One of the most widely discussed modeling languages for the description and design of mechatronic systems, under which automated production systems can be subsumed, is currently the Systems Modeling Language (SysML). It offers several language elements and constructs to describe a technical system's structure as well as its behavior and comprises a specialized extension to the Unified Modeling Language (UML), which mainly focuses on software systems. As a language profile that is based on the standard extension mechanisms, which UML provides, SysML itself can be further extended by additional *stereotypes* in order to introduce new, specialized language elements. The formal specification of *constraints* to these language elements, to their attributes and relations to each other using Object Constraint Language (OCL) furthermore enables the definition of design patterns for a system to be modeled that can be made available and checked in most of the currently available tools.

For modeling a system's elements (cf. system aspect 'Elements' in Fig. 2), the SysML provides the language element *Block* which provides means to describe key factors of the elements as parameters and, by specifying constraints for these parameters, also target values that need to be fulfilled as a design goal.

Like a system's elements, a system itself can be modeled as a (composite) *Block* in SysML with *Ports* defining the system's interfaces to neighboring systems or its environment. In order to specify design patterns, constraints can be specified which for one thing define the aspired extend of a system's interface (e.g. amount and/or configuration of these ports) to its environment, i.e. the interface over which turbulences from outside can influence the system (cf. system aspect 'Environment Sensors' in Fig. 2), as well as a systems inner reaction to these turbulences, i.e. its possible inner reconfigurations do to disturbances from outside, which e.g. cause a sensor defect. The design goals / patterns regarding these inner reactions can be described as a structural space of action (cf. system aspect 'System Boundary' Fig. 2), e.g. the existence of redundant (soft-)sensors, as well as the requirement for a behavioral space of action (cf. system aspect 'Behavior/acting in Fig. 2), i.e. alternative behaviors in case of breakdowns of single system elements. For illustration purposes, a simplified meta-model of the Activity-Diagram of the SysML profile is shown in Fig. 3, where each *Activity* references from zero or an infinite number of (outgoing) *Edges* to following activities.

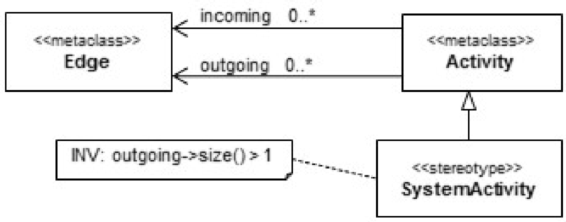

Fig. 3. Exemplary Extension to SysML for Change Capability by Design taking the system aspect "Behavior/acting" into account.

As an exemplary behavioral design pattern that demands at least two possible following activities for every activity of a system, i.e. one following activity for the normal operation and one for the case that an alternative behavior is necessary, the stereotype *SystemActivity* is introduced. By a constraint formulated in OCL, this stereotype constrains the number of elements in the set of outgoing edges to at least two.

For describing relations between a system's elements, several language constructs exist in SysML as well. In order to specify design patterns for the inner architecture of a system (cf. system aspect 'Relations' in Fig. 2), which aim a designing a change capable systems regarding this aspect, again, constraints can be introduced in order to define the amount and configuration of these relations. For example, if the modularity of the system is aspired as a design goal / pattern, these constraints can be formulated to ensure that the relations between a system's elements are minimized.

6. Summary

Change capability is a mandatory characteristic for evolvable systems, which facilitates the survivability of technical, social, or socio-technical systems. Thus far, however, no approaches for formal modeling of change capability or further system characteristics exist. Accordingly, an (virtual) ex ante investigation of system design alternatives is currently not possible with the common formal modeling languages.

As a possible and extendable modeling language, that allows for the description of automated production systems, the Systems Modeling Language (SysML) has been motivated and briefly discussed and the possibilities of this language for formulating design patterns for change capable (production) systems have been pointed out. However, the SysML represents only a semi-formal language. Although a wide range of formalizations of UML- and SysML-based approaches have been developed none existing approach covers all necessary aspects that need to be covered for an operationalization of change capability that can be used for an approach for "Change Capability by Design". The same holds for the formalization of design patterns to change capability, were currently only few approaches exist. Future works will further investigate the SysML as a modeling language in the light of the operationalization for change capability presented in this paper.

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