

Quantifying the “Amount of Change” to Enable Inconsistency Risk Evaluation in Cross-Generational Cyber-Physical Systems Engineering

Lars Gesmann*, Gabrihel Monagas Martin, Maximilian Fischer, Stefan Eric Schwarz, Tobias Düser, Albert Albers

IPEK - Institute of Product Engineering | KIT - Karlsruhe Institute of Technology

* Corresponding author:

Lars Gesmann
IPEK - Institute of Product Engineering Kaiserstraße 10
76131 Karlsruhe
Geb. 10.23, room 806
☎ +49 721 608 48245
✉ lars.gesmann@kit.edu

Abstract

Quantifying the extent of engineering changes is essential for assessing inconsistency risk in cross-generational development of Cyber-Physical Systems (CPS), yet existing metrics remain largely domain- or artifact-specific. This paper develops a domain-independent basis for operationalizing the Amount of Change. Based on a systematic literature review, relevant metrics are identified, evaluated, and synthesized into a framework that integrates relative cross-generational deviation with the absolute extent of affected elements. Its applicability is demonstrated in a brake system case across requirements and functions, showing how Amount of Change can be quantified in a structured, comparable way across different view types.

Keywords

Cyber-Physical Systems, Change Impact Analysis, Engineering Change Metrics, Consistency Management, System Generation Engineering

1. Introduction

Engineering changes are a persistent source of effort and risk in the development of complex technical systems. In Cyber-Physical Systems (CPS), even local modifications may propagate across mechanical, electrical, and software-related artifacts, causing cross-domain inconsistencies, additional coordination effort, and project delays [1, 2].

This challenge is particularly relevant in System Generation Engineering (SGE), where new generations are derived from reference system elements through carryover, attribute, and principle variation [3]. Recent work conceptualizes inconsistency risk in CPS along the three dimensions Amount of Change, Knowledge about the Reference System Element, and Complexity. Among these, Amount of Change is central because it captures the extent of the intended modification itself [4].

However, a standardized and domain-independent operationalization of Amount of Change for cross-generational CPS development is still missing. Existing metrics are typically domain- or artifact-specific and therefore do not directly support transferable assessment in interdisciplinary development settings.

Against this background, this paper develops a domain-independent basis for quantifying Amount of Change in cross-generational CPS development. Existing metrics are identified and evaluated, synthesized into a transferable framework, and illustrated using a brake system case. The contribution is a metric logic that combines relative cross-generational deviation with the absolute extent of affected elements and thus provides a first structured basis for integrating Amount of Change into inconsistency risk assessment in CPS.

2. Background

2.1. Cyber-Physical Systems and System Generation Engineering

CPS integrate mechanical, electrical, and software-based elements and therefore require coordination across multiple interdependent engineering view types and domains (Gesmann et al., 2025a). In contrast to mono-disciplinary systems, CPS development involves a high degree of structural and organizational complexity because knowledge, models, and tools are distributed across several engineering domains [5], [6]. As a consequence, modifications introduced in one domain often affect other domains indirectly, which makes cross-domain alignment a central challenge in development projects [7].

To describe the development of such systems, the understanding of SGE is useful. According to [3], new system generations are not developed from scratch, but on the basis of reference systems. SGE assumes that system elements of a new generation are derived from reference system elements and realized through three fundamental types of variation: carryover variation, attribute variation, and principle variation. Carryover variation denotes the reuse of a subsystem with only interface adaptations, attribute variation modifies selected properties of an existing subsystem, and principle variation changes the internal elements or links of a subsystem more fundamentally. [3]

This perspective is relevant in our context because it links technical modifications to cross-generational evolution. Accordingly, SGE provides a useful conceptual basis for understanding how changes emerge between generations, but it does not in itself provide a standardized quantitative measure for the extent of those changes.

2.2. Engineering Changes and Change Propagation

Engineering changes are an inherent part of system development and can substantially affect time, cost, and quality, especially in highly coupled CPS contexts [8], [9]. These changes may affect structures, behaviors, functions, or relations between system elements, and their consequences can range from isolated local adjustments to broad systemic repercussions [9].

For this reason, change management cannot be reduced to documenting modifications; it must also account for how changes spread through a system and across development domains [10].

A central concept in this regard is change propagation. [2] describe how components within a system can act as absorbers, carriers, or multipliers of change. Absorbers reduce the effects of surrounding changes, carriers transmit them without substantially altering their magnitude, and multipliers intensify propagation by triggering additional changes. Depending on the interaction of these roles, propagation patterns may take the form of ripples, blossoms, or avalanches. [2]

For the present research, this understanding is important because the amount of change is not only a descriptive property of modification, but also a likely driver of propagation behavior. In cross-generational CPS development, larger or more invasive modifications increase the probability that additional artifacts, interfaces, and domain models will have to be adapted as well. Quantifying the amount of change is therefore a necessary step toward a more systematic anticipation of cross-domain consequences.

2.3. Inconsistency Risk in CPS Development

A key risk of engineering changes in CPS development is the emergence of inconsistencies between domain-specific models, artifacts, and views [11]. Because different engineering disciplines rely on their own representations, tools, and abstraction levels, cross-domain consistency cannot be taken for granted and must be actively maintained throughout development. This challenge becomes even more pronounced when several system variants and generations have to be developed and maintained in parallel [12].

Approaches such as Model-Based Systems Engineering (MBSE) aim to support consistency by treating models as primary development artifacts and by connecting information across disciplines [13]. However, standard MBSE approaches often struggle to ensure full consistency in CPS because such systems must be represented across multiple abstraction levels and views, while still preserving domain-specific requirements and autonomy. Similar limitations apply to the Single Underlying Model (SUM), which seeks consistency through unified formal modeling but becomes difficult to scale in highly heterogeneous CPS contexts [12].

To address these limitations, [14] propose the Virtual Single Underlying Model (V-SUM), which virtualizes semantic overlaps between engineering models while keeping the original domain models separate. This makes it possible to manage consistency relations without forcing all artifacts into one monolithic representation [14]. Nevertheless, even with such consistency-oriented approaches, the practical assessment of change-related risk still requires a better understanding of how strongly a planned modification affects the evolving system. In other words, consistency management approaches address how relations between models can be maintained, but they do not by themselves provide a domain-independent metric for quantifying the amount of change that threatens those relations.

2.4. Amount of Change as a Dimension of Risk Assessment

To support the risk-oriented assessment of planned changes in CPS, prior work frames inconsistency risk in CPS along the three dimensions Amount of Change, Knowledge about the Reference System Element, and Complexity. Within this model, Amount of Change captures the extent of the intended modification and must be distinguished from both the structural difficulty of the system context and the available knowledge about the reference element. [4]

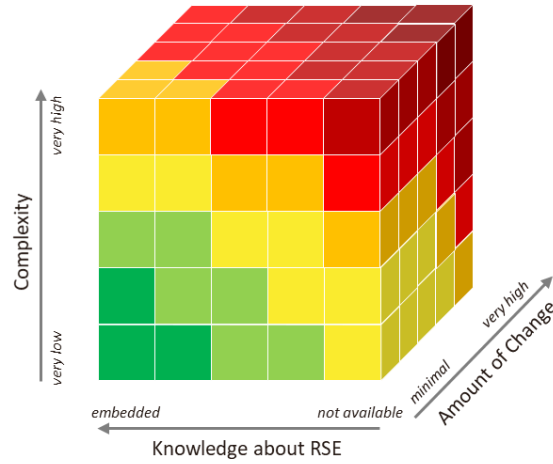


Figure 1: The Amount of Change as a dimension of the three-dimensional risk matrix for assessing inconsistency risks [4].

Despite its relevance, the Amount of Change has so far lacked a standardized and domain-independent operationalization for cross-generational CPS development. Existing work provides methods for evaluating complexity in CPS contexts and offers ways to reason about knowledge availability, but comparable approaches for objectively quantifying the amount of change across engineering domains remain missing. Moreover, many existing change metrics have been developed for specific domains or view types and therefore cannot be transferred directly to interdisciplinary CPS development without further synthesis and abstraction. This gap motivates the research presented in this paper and provides the basis for the methodological approach described in the following section.

3. Research Approach

The research follows the Design Research Methodology (DRM) to develop and demonstrate a domain-independent basis for quantifying the Amount of Change in cross-generational CPS development. This framing is suitable because the objective is not only to analyze an existing problem, but also to derive a methodological artifact and illustrate its applicability in a technical case context. [15]

The research process comprised three main steps. First, a systematic literature review was conducted to identify existing metrics and frameworks related to engineering change quantification across different engineering domains. Scopus was selected as the primary database because of its interdisciplinary coverage, and the search process yielded 1,646 initial records. After staged screening at title, abstract, and full-text level, 15 publications were retained as the final core sample for detailed analysis.

Second, the identified metrics were evaluated with regard to their suitability for operationalizing the Amount of Change in CPS development. Following the logic documented in the underlying thesis and abstract, the assessment considered criteria such as domain coverage, applicability to change propagation contexts, quantifiability, and transferability across engineering domains. This step was intended to determine which underlying metric principles are sufficiently general to support a domain-independent operationalization of the Amount of Change.

Third, the most suitable principles were synthesized into a domain-independent framework and applied to a brake system case example spanning successive generations and variants [16]. The case application serves as an initial demonstration of how the synthesized logic can be instantiated for CPS view types such as functions and requirements.

4. Quantifying the Amount of Change

4.1. Understanding the Amount of Change

To quantify the Amount of change, we need to have a common understanding of it. In this paper the Amount of Change refers to the extent to which a system generation differs from its previous generation with respect to selected engineering view types and their relevant properties. It thus captures how much of a system is retained, modified, added, or removed during cross-generational development.

Before its operationalization, the Amount of Change must be distinguished from related constructs. First, the Amount of Change is not identical to change impact, which concerns the consequences of a modification, for example in terms of affected dependencies, redesign effort, or propagation through neighboring system elements [2], [17]. Second, the Amount of Change is not equivalent to system complexity, which describes the structural and relational difficulty of the system context [4], [18].

4.2. Evaluation of existing metrics

To support cross-generational CPS development, the Amount of Change must be quantifiable, transferable across heterogeneous view types, and interpretable from different engineering domains [4], [5], [19]. Against this background, 14 change-related metrics from the literature were evaluated using the criteria shown in Table 1.

Table 1: Comparison of the identified metrics based on different criteria.

Author	Domain Coverage	Propagation	Facility	Quantification	Transferability
Clarkson et al., [20]	●	●	○	○	●
Koh et al., [21]	●	●	○	○	●
Eltaief et al., [22]	◐	●	◐	●	◐
Nejati et al., [17]	◐	●	○	●	◐
Masmoudi et al., [23]	◐	●	◐	●	◐
Chua and Hossain, [24]	○	●	◐	○	○
Sepahvand et al., [25]	◐	◐	◐	◐	◐
Champagne and Carver, [26]	◐	◐	○	◐	○
Sun et al., [27]	●	●	○	○	●
Hanna et al., [28]	○	◐	◐	◐	○
Suh et al., [29]	●	●	◐	○	●
Nowak-Meitingner et al., [30]	◐	◐	●	◐	○
Ouertani, [31]	◐	◐	◐	◐	◐
Wong and Wynn, [19]	◐	○	●	●	●

● fully satisfied ◐ partially satisfied ○ not satisfied

The review shows that no single metric provides a sufficiently transferable and domain-independent operationalization of Amount of Change for CPS. Broadly, these metrics can be grouped into two main categories. Consequence-oriented metrics, which describe how changes spread through a system and which components are particularly sensitive or exposed [2], [21], whereas structure-oriented metrics quantify the change itself in relative or absolute

terms [17], [19]. For operationalizing Amount of Change, the most suitable candidates are therefore those that directly quantify the extent of modification and remain interpretable beyond a single narrow domain context.

From this perspective, the Commonality Index and Impact Magnitude emerge as the strongest foundations for synthesis. The Commonality Index is especially valuable because it captures relative cross-generational deviation. It answers the question of how strongly a successor generation differs from its previous generation under a selected scope [19]. This aligns directly with SGE, where change is inherently understood in relation to a reference system [3]. Impact Magnitude on the other hand, captures absolute change extent by measuring the cardinality of the affected set within a defined scope of analysis [17]. Together, they cover the two key dimensions of Amount of Change: how different the new generation is, and how much of the view type is actually affected.

4.3. Synthesis

The synthesis combines two complementary principles. From the Commonality Index, it adopts the idea that cross-generational change should be expressed relative to a baseline and interpreted across selectable comparison view [19]. From Impact Magnitude, it adopts the idea that the amount of change should also be expressed through the size of the affected set in absolute terms [17].

The first dimension captures relative deviation between a current generation and its successor generation by quantifying the share of units that remain unchanged versus those that are modified, added, or removed under a selected comparison view, for example requirements or functions. In the framework, this dimension is expressed through the Commonality C, which denotes the proportion of retained units in the comparison set and thereby reflects how closely a successor generation still aligns with its reference system [19]. The second dimension captures the absolute extent of change by counting all units that are affected by the transition, irrespective of whether they are newly introduced, altered, or removed. This dimension is expressed through the absolute change extent Impact Magnitude (IM), which denotes the cardinality of the affected set and provides a direct indication of how much of the view type is touched by a modification [17].

To ensure comparability across different cross-generational transitions, the Impact Magnitude is normalized. This is done by dividing the Impact Magnitude of the current cross-generational transition by the maximum value of all cross-generational transitions within a given view type. This yields a normalized impact magnitude (IM_{norm}). Based on these components, the Amount of Change (AoC) for a given transition and view type is quantified as: $AoC = (1-C) \times IM_{norm}$.

The implementation of the framework follows four steps. First, the relevant view type and unit of comparison are defined. Second, each unit is classified according to whether it is retained, modified, added, or removed between the current generation and the successor generation. Third, the relative deviation is derived from the proportion of unchanged and changed units in the comparison set, corresponding to the commonality-oriented logic. Fourth, the absolute affected scope is determined by counting the affected units, corresponding to the impact-magnitude-oriented logic. Finally, both views are interpreted jointly to characterize the Amount of Change.

5. Application to a Brake System Case Example

To illustrate the applicability of the synthesized framework, it was applied to a brake system research platform that represents successive generations and variants of a CPS [16]. The case serves as an initial demonstration rather than a comprehensive validation.

For the analysis each transition between generations is evaluated from two view types: requirements (Req.) and functions (Func.). Within each view type, the relevant units from the reference and successor generation are classified as retained, modified, added, or removed, based on the detailed lists documented for the generations of the brake system research platform. This classification provides the input needed to derive the Commonality (C) and Impact Magnitude (IM) according to the framework introduced in chapter 4.3.

As part of this study, we examined the various development paths of the three generations of braking systems and analyzed how the requirements and functions have changed across the generations (see Table 2).

Table 2: Quantified Amount of Change for two view types across different generations of braking systems.

Transition	View type	Retained	Modified	Added	Removed	C	IM	IM _{norm}	AoC
G _n to G _{n+1,V1}	Req.	34	2	4	0	0.85	6	0.75	0.11
	Func.	23	0	2	0	0.92	2	0.29	0.02
G _{n+1,V1} to G _{n+2,V1}	Req.	37	0	5	1	0.86	6	0.75	0.10
	Func.	24	0	1	1	0.92	2	0.29	0.02
G _n to G _{n+1,V2}	Req.	34	2	4	0	0.85	6	0.75	0.11
	Func.	23	0	4	0	0.85	4	0.57	0.08
G _{n+1,V2} to G _{n+2,V2}	Req.	37	0	7	1	0.82	8	1.00	0.18
	Func.	26	1	1	1	0.90	3	0.43	0.04
G _{n+1,V2} to G _{n+2,V3}	Req.	37	0	7	1	0.82	8	1.00	0.18
	Func.	22	1	1	5	0.76	7	1.00	0.24

The table shows that all transitions preserve a substantial share of unchanged units, with commonality values between 0.76 and 0.92, while differing in the extent of affected units and resulting AoC. The AoC evolves differently across the two view types. Within the requirement view, the later transitions G_{n+1,V2} to G_{n+2,V2} and G_{n+1,V2} to G_{n+2,V3} reach the highest Impact Magnitude, leading to AoC values of 0.18 and indicating comparatively strong specification-side interventions in these paths. Within the function view, change is more concentrated: the transition G_{n+1,V2} to G_{n+2,V3} yields the highest functional AoC (0.24). Rather than suggesting that one view type is universally more extensive than the other, these results underline that the AoC must be interpreted per view type and that some transitions are driven primarily by adjustments on the requirement level, whereas others involve stronger functional adjustments.

The application indicates that the framework is able to quantify the Amount of Change in a structured and comparable way across multiple system generations and variants. This is relevant for the intended use of the framework in inconsistency risk assessment. At the same time, the results also confirm that the measured delta depends on the chosen view type, which supports the paper's argument that a domain-independent comparison logic must still be instantiated through view type-specific data.

6. Discussion

The case application demonstrates that the proposed framework provides a structured way to quantify the Amount of Change across successive generations of a CPS using view type-based information. By combining relative deviation from a reference generation with the absolute extent of affected elements, the framework transforms cross-generational differences into interpretable deltas and thereby complements predominantly qualitative descriptions of engineering change with a more explicit basis for comparison.

A key strength of the proposed framework is that it enables the Amount of Change to be represented as a quantified deviation between generations rather than as an intuitive or purely experience-based judgment. Thereby, the framework supports more consistent reasoning about how strongly a successor generation differs from its previous generation and creates a clearer basis for discussing change-related coordination effort and measuring inconsistency risks in CPS development.

The brake system case further shows that Amount of Change is not a uniform property of a cross-generational transition, but depends on the selected view type. A high Amount of Change for one view type does not necessarily mean that the other view types also have a high Amount of Change (e.g. the transition from $G_{n+1,V2}$ to $G_{n+2,V2}$). This is important because it underlines that a domain-independent quantification logic does not eliminate the need for view type-specific interpretation.

At the same time, the study has clear limitations. First, the application is restricted to requirements and functions. While this is sufficient to demonstrate the basic applicability of the framework, it does not yet show whether the same logic can be transferred without loss to other CPS-relevant artifacts such as interfaces, components, software structures, or further discipline-specific models. The claim of domain independence should therefore be understood as a methodological proposition that still requires broader empirical validation across additional view types and development contexts.

Second, the underlying research context describes inconsistency risk as emerging from the interaction between Amount of Change, Knowledge about the Reference System Element, and Complexity, but the current contribution operationalizes only the Amount of Change dimension itself. As a result, the interplay of these three dimensions remains unresolved, and the study does not yet show how a quantified Amount of Change translates into a concrete inconsistency risk level in practice.

Overall, the main contribution of the framework currently lies in providing a transparent and transferable basis for describing how extensive a change is, and thus supplies one essential input for future inconsistency risk assessment in cross-generational CPS development. The next step is therefore not to replace broader risk reasoning, but to integrate the quantified Amount of Change with the remaining dimensions of Knowledge and Complexity in a consistent assessment model.

7. Conclusion

This paper addressed the lack of a domain-independent basis for quantifying the Amount of Change in cross-generational CPS development. Since existing metrics either focus on consequences of change or remain tied to specific domains and view types, they do not by themselves provide a sufficiently transferable operationalization for interdisciplinary CPS contexts.

To address this gap, the paper evaluated existing change-related metrics and synthesized two complementary principles into a unified framework: relative deviation from a reference generation, represented through Commonality, and absolute affected scope, represented through Impact Magnitude and its normalization. On this basis, the Amount of Change was operationalized as $AoC = (1-C) \times IM_{norm}$, providing a structured way to characterize how strongly a successor generation differs from its previous generation with respect to a selected view type.

The brake system case illustrated that the framework can be instantiated for requirements and functions and can reveal different change patterns across generational transitions. In this sense, the contribution of the paper is not only the formal synthesis of existing metric ideas, but also the demonstration that cross-generational change can be described in a comparable and view type-sensitive way without reducing the analysis to a single engineering domain.

At the same time, the scope of the contribution should be interpreted carefully. The present work does not yet validate the framework across the full range of CPS-relevant view types, nor does it derive a complete inconsistency risk from Amount of Change alone. Rather, it establishes a methodological foundation for making Amount of Change more explicit, comparable, and discussable in interdisciplinary CPS development.

Future research should therefore extend the framework to additional engineering view types and validate its applicability beyond requirements and functions. In addition, the quantified Amount of Change must be integrated with the dimensions of Knowledge about the Reference System Element and Complexity in order to clarify their interaction and to enable a more complete inconsistency risk assessment model for changes in CPS development.

Acknowledgements

This paper is funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) – SFB 1608 – 501798263.

References

- [1] FRICKE, ERNST; GEBHARD, BERND; NEGELE, HERBERT; IGENBERGS, EDUARD: Coping with changes: Causes, findings, and strategies. In: *Systems Engineering*, Vol. 3 (2000), Nr. 4, pp. 169-179 – DOI: 10.1002/1520-6858(2000)3:4<169:AID-SYS1>3.0.CO;2-W
- [2] ECKERT, CLAUDIA; CLARKSON, P. JOHN; ZANKER, WINFRIED: Change and customisation in complex engineering domains. In: *Research in Engineering Design*, Vol. 15 (2004), Nr. 1, pp. 1-21 – DOI: 10.1007/s00163-003-0031-7
- [3] ALBERS, ALBERT; RAPP, SIMON: Model of SGE: System generation engineering as basis for structured planning and management of development. In: KRAUSE, D.; HEYDEN, E. (eds.): *Design methodology for future products*. Cham: Springer International Publishing, 2022, pp. 27-46 – DOI: 10.1007/978-3-030-78368-6_2
- [4] GESMANN, LARS; FISCHER, MAXIMILIAN; MARTIN, ALEX; DÜSER, TOBIAS; ALBERS, ALBERT: Towards a standardized evaluation framework for engineering changes in the model of SGE - system generation engineering. In: *19th CIRP conference on intelligent computation in manufacturing engineering (CIRP ICME 25)*, in press
- [5] REUSSNER, RALF; SCHAEFER, INA; BECKERT, BERNHARD; KOZIOLEK, ANNE; BURGER, ERIK: Consistency in the view-based development of cyber-physical systems (convide). In: *2023 ACM/IEEE international conference on model driven engineering languages and systems companion (MODELS-c)*, IEEE, 2023, pp. 83-84 – DOI: 10.1109/MODELS-C59198.2023.00026
- [6] ALBERS, ALBERT: *Rethinking and Reframing Engineering. Challenges, Application Scenarios and the New Advanced Systems Engineering Model*, acatech IMPULSE. Munich, 2023 – DOI: 10.48669/aca_2023-21
- [7] MARTIN, ALEX; PFEIFER, STEFAN; ENGE, ENRICO; SCHABBERHARD, MARIUS; ALBERS, ALBERT: Communication approach for the model-based engineering change management. In: *Procedia CIRP*, Vol. 136 (2025), pp. 734-739 – DOI: 10.1016/j.procir.2025.08.125
- [8] KOH, EDWIN C. Y.: A study on the requirements to support the accurate prediction of engineering change propagation. In: *Systems Engineering*, Vol. 20 (2017), Nr. 2, pp. 147-157 – DOI: 10.1002/sys.21385
- [9] JARRATT, T. A. W.; ECKERT, C. M.; CALDWELL, N. H. M.; CLARKSON, P. J.: Engineering change: an overview and perspective on the literature. In: *Research in Engineering Design*, Vol. 22 (2011), Nr. 2, pp. 103-124 – DOI: 10.1007/s00163-010-0097-y
- [10] ECKERT, CLAUDIA; DE WECK, OLIVIER; KELLER, RENE; CLARKSON, P. JOHN: Engineering change: drivers, sources, and approaches in industry. In: *Proceedings of ICED 09, the 17th International Conference on Engineering Design*, Vol. 4 (2009) – ISBN: 978-1-904670-08-7, pp. 47-58
- [11] GESMANN, LARS; FISCHER, MAXIMILIAN; LAUFF, ANNA; VÖLK, THOMAS; DÜSER, TOBIAS; ALBERS, ALBERT: Challenges in the Development of Cyber-Physical Systems – Insights from Research and Industrial Practice. In: *Procedia Computer Science, 7th International Conference on Industry of the Future and Smart Manufacturing*, Vol. 277 (2026), pp. 1963-1972 – DOI: 10.1016/j.procs.2026.02.234
- [12] ALBERS, ALBERT; SCHAEFER, INA; GESMANN, LARS; OCHS, PHILIP; FISCHER, MAXIMILIAN; PETT, TOBIAS; SCHWARZ, STEFAN ERIC: Consistency in Cross-Generational Engineering of Cyber-Physical Systems. In: *Proceedings of the 35th Symposium Design for X (DFX2024)*, The Design Society, 2024, pp. 085-094 – DOI: 10.35199/dfx2024.09
- [13] HUSUNG, STEPHAN; WEBER, CHRISTIAN; MAHBOOB, ATIF; KLEINER, SVEN: Using Model-Based Systems Engineering for Need-Based and Consistent Support of the Design Process. In: *Proceedings of the Design Society*, Vol. 1 (2021), pp. 3369-3378 – DOI: 10.1017/pds.2021.598

- [14] KLARE, HEIKO; KRAMER, MAX E.; LANGHAMMER, MICHAEL; WERLE, DOMINIK; BURGER, ERIK; REUSSNER, RALF: Enabling consistency in view-based system development – The Vitruvius approach. In: *Journal of Systems and Software*, Vol. 171 (2021), Nr. 110815 – DOI: 10.1016/j.jss.2020.110815
- [15] BLESSING, LUCIENNE T.M.; CHAKRABARTI, AMARESH: *DRM, a design research methodology*. London: Springer London, 2009 – ISBN 978-1-84882-586-4
- [16] GESMANN, LARS; SCHWARZ, STEFAN ERIC; VÖLK, THOMAS; BAUSE, KATHARINA; GRYCZ, PATRICK; URBANO, FRANCESCO; DÜSER, TOBIAS; ALBERS, ALBERT: Ensuring consistency in CPS engineering braking systems as a research platform. In: *Proceedings of the 11th International Symposium on Development Methodology*, (2025)
- [17] NEJATI, MAHTAB; ALFADEL, MAHMOUD; MCINTOSH, SHANE: Understanding the implications of changes to build systems. In: *Proceedings of the 39th IEEE/ACM international conference on automated software engineering (ASE '24)*, IEEE, 2024, pp. 1421-1433 – DOI: 10.1145/3691620.3695514
- [18] SINHA, KAUSHIK; DE WECK, OLIVIER L.: A network-based structural complexity metric for engineered complex systems. In: *2013 IEEE International Systems Conference (SysCon)*, 2013, pp. 426-430 – DOI: 10.1109/SysCon.2013.6549917
- [19] WONG, FOO SHING; WYNN, DAVID C.: A new method to assess platform changes over successive generations of product variants from multiple design perspectives. In: *Proceedings of the Design Society: International Conference on Engineering Design*, Vol. 1 (2019), Nr. 1, pp. 2931-2940 – DOI: 10.1017/dsi.2019.300
- [20] CLARKSON, JOHN; SIMONS, CAROLINE; ECKERT, CLAUDIA: Predicting change propagation in complex design. In: *Journal of Mechanical Design*, Vol. 126 (2004), Nr. 5, pp. 788-797 – DOI: 10.1115/1.1765117
- [21] KOH, EDWIN C.Y.; CALDWELL, NICHOLAS H.M.; CLARKSON, P. JOHN: A technique to assess the changeability of complex engineering systems. In: *Journal of Engineering Design*, Vol. 24 (2013), Nr. 7, pp. 477-498 – DOI: 10.1080/09544828.2013.769207
- [22] ELTAIEF, AMENI; BEN MAKHLOUF, AICHA; BEN AMOR, SABRINE; REMY, SÉBASTIEN; LOUHICHI, BORHEN; EYNARD, BENOIT: Engineering change risk assessment: Quantitative and qualitative change characterization. In: *Computers in Industry*, Vol. 140 (2022), Nr. 103656 – DOI: 10.1016/j.compind.2022.103656
- [23] MASMOUDI, MAHMOUD; LECLAIRE, PATRICE; ZOLGHADRI, MARC; HADDAR, MOHAMED: Change propagation prediction: A formal model for two-dimensional geometrical models of products. In: *Concurrent Engineering*, Vol. 25 (2017), Nr. 2, pp. 174-189 – DOI: 10.1177/1063293X17698192
- [24] CHUA, D. K. H.; HOSSAIN, M. A.: Predicting change propagation and impact on design schedule due to external changes. In: *IEEE Transactions on Engineering Management*, Vol. 59 (2012), Nr. 3, pp. 483-493 – DOI: 10.1109/TEM.2011.2164082
- [25] SEPAHVAND, REZA; AKBARI, REZA; HASHEMI, SATTAR; BOUSHEHRIAN, OMID: An effective model to predict the extension of code changes in bug fixing process using text classifiers. In: *Iranian Journal of Science and Technology, Transactions of Electrical Engineering*, Vol. 46 (2022), Nr. 1, pp. 257-274 – DOI: 10.1007/s40998-021-00458-1
- [26] CHAMPAGNE, JOB M.; CARVER, DORIS L.: Measuring software change impact using requirement dependencies. In: *2021 IEEE/ACIS 19th international conference on software engineering research, management and applications (SERA)*, IEEE, 2021, pp. 58-65 – DOI: 10.1109/SERA51205.2021.9509272
- [27] SUN, YIWEI; WANG, YAO; ZHANG, XIAN; CHEN, DENGKAI: A risk prediction method for change propagation based on industrial design network evolution. In: *Journal of Computational Design and Engineering*, Vol. 12 (2025), Nr. 8, pp. 361-381 – DOI: 10.1093/jcde/qwaf084
- [28] HANNA, AWAD S.; RUSSELL, JEFFREY S.; VANDENBERG, PAUL J.: The impact of change orders on mechanical construction labour efficiency. In: *Construction Management and Economics*, Vol. 17 (1999), Nr. 6, pp. 721-730 – DOI: 10.1080/014461999371060
- [29] SUH, EUN SUK; DE WECK, OLIVIER L.; CHANG, DAVID: Flexible product platforms: framework and case study. In: *Research in Engineering Design*, Vol. 18 (2007), Nr. 2, pp. 67-89 – DOI: 10.1007/s00163-007-0032-z
- [30] NOWAK-MEITINGER, ANNA M.; MAYER, JAN; KISHOR MARDE, SANJANA; JOCHEM, ROLAND: Identifying uncertainty in large-scale industry 4.0 software projects through model-based requirements engineering. In: Rodríguez-Rodríguez, R., Ducq, Y., Leon, RD., Romero, D. (eds.): *Enterprise Interoperability X*, Vol. 11 (2024), Cham: Springer International Publishing, pp. 13-24 – DOI: 10.1007/978-3-031-24771-2_2
- [31] OUERTANI, M. Z.: Supporting conflict management in collaborative design: An approach to assess engineering change impacts. In: *Computers in Industry*, Vol. 59 (2008), Nr. 9, pp. 882-893 – DOI: 10.1016/j.compind.2008.07.010