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Structured overview of methodologies for assessing assembly complexity

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ABSTRACT: This paper provides a structured overview of methods for assessing assembly complexity in manufacturing. A systematic literature review classifies approaches as product-, information-, or system-centered, each reflecting distinct sources of complexity and application contexts. A four-dimensional scheme enables consistent comparison. The results highlight methodological gaps and support future development of scalable, integrable models for planning and decision-making in high-variety production environments.

KEYWORDS: complexity, complex systems, variant management, design methods, assembly complexity

1. Introduction

Manufacturing companies have recently faced increasing demands for customized products, leading to greater product and process complexity. The issue of assembly complexity has received considerable attention throughout the years. Many studies have shown that assembly complexity has a direct effect on the occurrence of product defects and thus on quality costs (Favi & Germani, 2012; Genta et al., 2018; Hinckley, 1994; Rodriguez-Toro et al., 2003; Shibata, 2002; Su et al., 2010; Verna et al., 2022; Verna et al., 2023). Assembly complexity is a broad concept encompassing a set of product, process, and environmental factors that may affect how difficult it is to complete an assembly process. A definition was provided by Samy and ElMaraghy (2010), who described it as "the degree to which the individual parts/subassemblies contain physical attributes that cause difficulties during the handling and insertion processes in manual or automatic assembly." Complexity therefore affects both the physical and cognitive effort required from the operator during assembly.

Over the years, numerous attempts have been made to define objective and quantifiable measures of complexity. Researchers have approached assembly complexity from different perspectives (Alkan et al., 2018; Efthymiou et al., 2016; ElMaraghy et al., 2012). Some focus on physical, geometrical, and structural characteristics of products, while others adopt a broader view that includes process-related and systemic factors. These diverse approaches reflect the multidimensional nature of complexity in manufacturing. As the number of product variants increases, so too does the complexity of internal production and logistics processes (Keuper & Schomann, 2008). According to DIN 199, a variant is defined as a product that has a similar form and/or function to the existing product and shares with it a high proportion of identical components or assemblies (DIN Deutsches Institut für Normung e. V., 2024). Due to internal and external influences on production systems, a fundamental variety of variants is often unavoidable, leading to variant-related costs that arise across factory systems (Hingst & Nyhuis, 2022). These costs rarely occur precisely where they are caused: 50 – 80% of variant-driven costs arise in production and logistics (Fischer, 2008). Moreover, companies often struggle to distinguish between value-adding and value-destroying variants at an early stage (Keuper & Schomann, 2008). A comprehensive understanding of variant-related costs and their effects is essential for factory planners in order to take targeted measures (Biedermann, 2016). Variety-induced complexity, driven by the number of product variants offered, has become a central challenge in manufacturing. Increasing product variety

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typically leads to greater component diversity and more differentiated manufacturing processes (Salvador et al., 2002; Salvador et al., 2004). Product variety contributes to the structural complexity of manufacturing and logistics systems and is intertwined with the interdependencies of their elements, including process and supplier diversity (Chryssolouris et al., 2013). Plant managers, in particular, observe the impact of product complexity on process complexity through more demanding production planning and scheduling (Chryssolouris et al., 2013). It is essential to analyze all existing methods to obtain an overview of the numerous developed approaches, since this makes it possible to identify the existing gap that contributes to undetected complexity and related costs in variant-rich production. With that in mind, this study addresses the following research question: *Which methods exist for assessing assembly complexity that support the production planning process and reduce complexity-induced cost in production?*

The objective of this paper is threefold:

1. **Identification**: Provide a structured overview of existing methods and research approaches for evaluating assembly complexity and related costs within manufacturing contexts.
2. **Analysis**: Classify these methods based on their methodological orientation, application area, and considered complexity factors.
3. **Evaluation**: Identify the need for further research in the development of complexity assessment methods, particularly in planning-related applications.

2. Research method

To answer the above research question, it is necessary to apply a comprehensive approach combining a systematic literature review (SLR) with snowballing method and a structured summary according to the considered factors.

Both steps are described in more detail below.

2.1. Systematic literature review process

The search for literature (Figure 1) was performed in two databases - Scopus and Web of Science (WoS) - in August 2025, with a first iteration based on a systematic search string that includes a filtering based on PRISMA (Moher, D. et al., 2009) and a second iteration analyzing the cross-references of publications found through the search string in the first iteration.

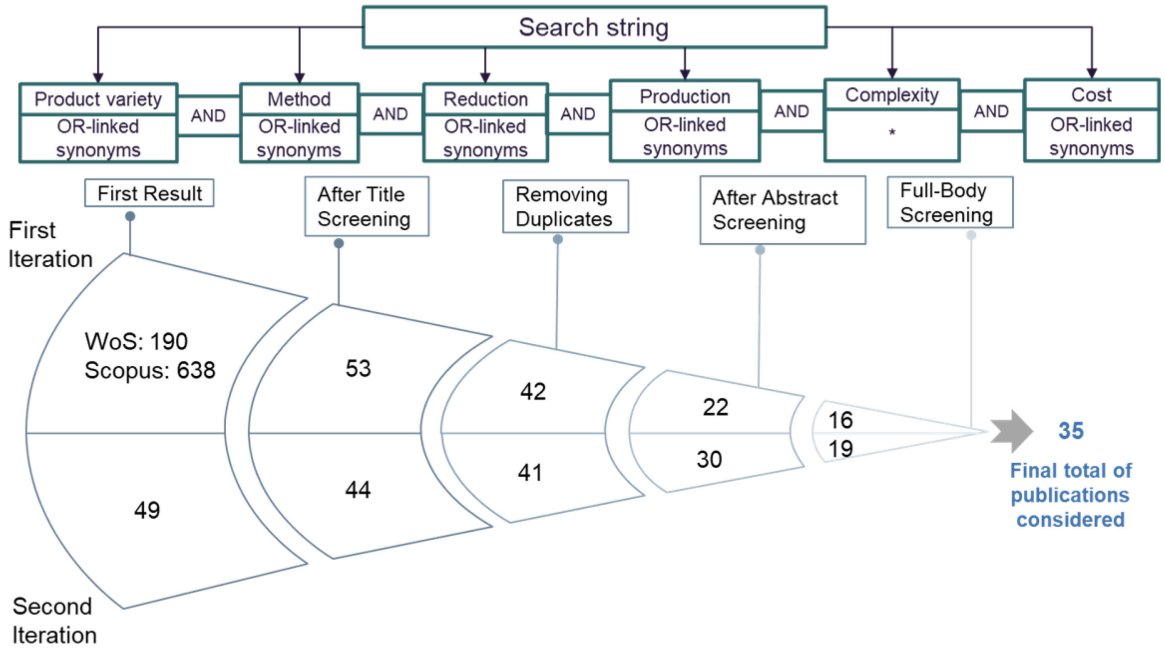


Figure 1. Search string and screening process results

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Web of Science:
TS=((“product variety” OR “product family” OR “product variant” OR variet* OR variant*) AND (“method” OR “framework” OR “model” OR “strategy” OR “approach” OR “technique”) AND (“reduction” OR “management” OR “control” OR “planning”) AND (“production” OR “manufacturing” OR “fabrication” OR “assembly”) AND complexit* AND (“cost” OR “expense” OR “price”))
Scopus:
TITLE-ABS-KEY ((“product variety” OR “product family” OR “product variant” OR “variety*” OR “*variety” OR “variant*” OR “*variant”) AND (“method” OR “framework” OR “model” OR “strategy” OR “approach” OR “technique”) AND (“reduction” OR “management” OR “control” OR “planning”) AND (“production” OR “manufacturing” OR “fabrication” OR “assembly”) AND (“complexity*” OR “*complexit”) AND (“cost” OR “expense” OR “price”))

2.2. Classification elements of methodologies

A wide range of methods has been developed to assess assembly complexity in manufacturing, but these methods differ significantly in their approach, target domain, and aims, as well as the complexity factors they address. To support the analysis and answer the research question, each identified complexity assessment method is classified using a structured overview table. This table is designed to highlight key dimensions that allow for a consistent and transparent comparison across diverse approaches. Specifically, the classification is based on three core dimensions:

a) First, the **approach** refers to the general perspective from which complexity is assessed. It distinguishes whether the method focuses on the product itself (product-centered), on the informational structure and diversity that must be managed during the assembly process (information-centered), or on the broader production system and its dynamics (system-centered).
b) Second, the **target domain and aim** describe the context in which the method is applied and its intended purpose. This includes the industrial or operational setting (e.g., assembly planning, product design, layout optimization) and the specific goal of the method, such as reducing complexity, predicting defects, or supporting decision-making.
c) Third, the classification also considers the main **complexity factor categories** and their associated attributes. Categories represent overarching dimensions: These serve as structural frameworks for organizing the specific attributes considered to quantify complexity, ranging from physical properties (e.g., size, weight, symmetry) and connection types to informational indicators (e.g., entropy, uncertainty) and human-related factors (e.g., mental workload, ergonomic strain).

Together, these three dimensions provide a comprehensive and consistent structure for analyzing the landscape of complexity assessment methods. This structure should provide a clear understanding of how different approaches conceptualize and operationalize complexity, and the aim is to form the basis for identifying methodological patterns, strengths, and areas for future development.

3. Structured overview of the assembly complexity assessment methods

To provide a transparent comparison of existing complexity assessment methods, this section presents a structured overview of the three approaches: product-centered, information-centered, and system-centered. Each approach is summarized in detail through dedicated overview tables (see Table 1, Table 2, and Table 3), highlighting the target domain, aim, and key complexity assessment categories.
To enhance readability and provide a consolidated overview, the tables are followed by a more detailed synthesis of the complexity factor attributes. These attributes are grouped according to the overarching categories presented in the tables above. While the tables primarily indicate the categorical structure, the subsequent section elaborates on the specific attributes assigned to each category.

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3.1. Product-centered approaches

Table 1. Structured overview of product-centered complexity assessment approaches

No.	Year	Method	Target domain	Aim	Complexity factor category
1	1993	**Hinckley**	Manufacturing and product design quality management	Evaluate and reduce defects caused by variation, human error, and design/process complexity	Variation Human Error Design/Process Complexity
2	1994	**Ben-Arieh**	Assembly process planning and design evaluation	Quantitatively assess the difficulty of individual and sequential assembly operations to optimize assembly sequence and orientation	Geometry-Based Parameters Non-Geometrical Parameters
3	2002	**Shibata**	Globally distributed manufacturing and assembly quality management	Evaluate and compare assembly complexity across international production sites to improve global quality consistency	Assembly Process Complexity Product Design Complexity Human and Organizational Factors Quality Performance Metrics
4	2010	**Su et al.**	Manual assembly quality control in electromechanical manufacturing	Predict operator-induced defect rates using complexity factors to improve assembly quality and reduce human error	Process-Based Complexity Design-Based Complexity
5	2012	**Mathieson et al.**	Early-stage product design and assembly time estimation	Predict assembly time using graph-based complexity metrics derived from system architecture, without detailed geometric data	Size Metrics Path Length Metrics Decomposition Metrics
6	2014	**Sinha**	Cyber-physical systems design and architecture	Quantify structural complexity to improve system design decisions, robustness, and lifecycle performance	Structural Complexity Dynamic Complexity Organizational Complexity
7	2018	**Alkan**	Industrial product design and early-stage assembly planning	Quantitatively assess structural assembly complexity to improve design decisions and reduce integration effort	Component Complexity Liaison Complexity Topological Complexity
8	2018	**Genta et al.**	Assembly manufacturing and quality inspection design	Predict defect rates based on product complexity to optimize inspection strategies, especially for short-run production	Process-Based Complexity Design-Based Complexity
9	2019	**Alkan**	Manual product design and planning	Evaluate how product design complexity relates to perceived assembly difficulty, combining objective and subjective factors	Complexity of Part Handling Attributes Complexity of Part Fitting Attributes Topological Complexity
10	2022	**Verna et al.**	Electromechanical product assembly and quality prediction	Predict defect rates using a fully objective structural complexity model, avoiding expert-based subjectivity	Part Complexity Connection Complexity Topological Complexity

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3.2. Information-centered approaches

Table 2. Structured overview of information-centered complexity assessment approaches

No.	Year	Method	Target domain	Aim	Complexity factor category
11	2003	**ElMaraghy and Urbanic**	Manufacturing system design and analysis (machining, assembly, production planning)	Quantify product and process complexity to identify simplification opportunities and support system sensitivity analysis	Product Complexity Process Complexity
12	2003	**Fujimoto et al.**	Assembly process design across product families in manufacturing	Evaluate and manage complexity caused by product variety using entropy-based metrics across design stages	Product Structure Planning Basic Assembly Process Planning Assembly Technology Planning
13	2004	**ElMaraghy and Urbanic**	Manufacturing operations and human-centric system design	Quantify operational complexity by integrating product, process, and human task effort to support system performance analysis	Core Complexity Dimensions Effort-Based Attributes Task Categories
14	2008	**Ameri et al.**	Engineering design evaluation and representation modeling	Quantify design product complexity using two independent measures—size and coupling—across multiple representation types	Size Complexity Coupling Complexity
15	2008	**Zhu et al.**	Manual mixed-model assembly lines	Quantify operator-induced complexity due to product variety using entropy-based choice modeling	Station-Level Complexity Factors System-Level Complexity Factors
16	2010	**Samy and ElMaraghy**	Product design and manufacturing, for manual and automatic assembly processes	Assess product assembly complexity by evaluating how part geometry and assembly attributes cause handling and insertion difficulties	Handling Attributes Insertion Attributes
17	2010	**Wang and Hu**	Mixed-model assembly systems with serial, parallel, and hybrid configurations	Quantify variety-induced complexity and analyze its impact on station reliability and system throughput	Station-Level Complexity System-Level Complexity Reliability & Throughput Factors
18	2012	**Samy and ElMaraghy**	Automated and hybrid assembly systems	Quantify structural complexity of assembly systems to support design decisions and reduce cost, time, and operational challenges	Station-Level Complexity System-Level Complexity
19	2012	**Samy and ElMaraghy**	Automated and hybrid assembly systems	Quantify and map product complexity to assembly equipment complexity to support design decisions and reduce system-level complexity	Part-Level Complexity System-Level Interaction
20	2013	**Wang et al.**	Mixed-model assembly systems with serial, parallel, and hybrid configurations	Minimize manufacturing complexity by optimizing product variant differentiation across parallel stations	Station-Level Complexity System-Level Complexity
21	2014	**Modrak et al.**	Mass-customized product assembly systems	Quantify configuration complexity based on the number of fixed and optional components to support product architecture decisions	Product Configuration Complexity Assembly Process Complexity
22	2015	**Park and Okudan Kremer**	Product family design and manufacturing systems	Quantify static complexity in product design and manufacturing, and analyze its impact on performance under different production strategies	Design Complexity Manufacturing Complexity Performance Impact Variables

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3.3. System-centered approaches

Table 3. Structured overview of system-centered complexity assessment approaches

No.	Year	Method	Target domain	Aim	Complexity factor category
23	2009	**Zaeh et al.**	Manual assembly operations in industrial settings	Develop a multi-dimensional complexity measure that accounts for human cognitive and experiential factors to improve task guidance and prediction	Temporal Factor Cognitive Factor Knowledge-Based Factor
24	2010	**Jenab and Liu**	Job shop manufacturing systems	Quantify relative manufacturing complexity and similarity among products using a graph-based model for cost estimation, resource planning, and product lifecycle analysis	Core Complexity Inputs Graph-Based Complexity Model
25	2011	**Abad and Jin**	Mixed-model manufacturing systems	Quantify input demand complexity, output product complexity, and process capability using entropy-based metrics inspired by communication systems	Input mix Ratio Output Mix Ratio Process Quality Mutual Information Normalized Capability Total Quality Rate
26	2013	**Chryssolouris et al.**	Manufacturing systems design and analysis	Investigate the relationship between system flexibility and complexity, and propose metrics for both	Static Complexity Dynamic Complexity
27	2013	**Al-Zuheri**	Manual assembly systems	Identify and model sources of structural and operational complexity to improve system design and performance	Operational Complexity Structural Complexity
28	2014	**ElMaraghy et al.**	Manufacturing system layout design	Quantify structural complexity of layouts using graph-based indices to support early-stage design decisions and trade-offs	Layout Complexity Indices
29	2016	**Mattsson et al.**	Operator-centered production system analysis	Assess perceived complexity at production stations using a Complexity Index to guide workplace design and support	Station Design Work Variance Disturbance Handling
30	2017	**Falck et al.**	Manual assembly in manufacturing, especially automotive and mixed-model production	The method aims to proactively assess basic manual assembly complexity—both cognitive and physical—to predict and prevent operator-induced quality errors	Physical Factors Cognitive Factors
31	2018	**Modrak and Soltysova**	Flow-oriented manufacturing systems and layout design	Develop a balanced operational complexity measure to support selection of optimal layout alternatives	Process Complexity Indicator Machine Complexity Indicator Balanced Complexity Indicator Complexity Equilibrium Point Product Variant Distribution
32	2019	**Busogi et al.**	Mixed model assembly lines	Quantify and minimize variety-induced manufacturing complexity through optimized product sequencing	Assembly Sequence Structure Sequence Entropy Operator Workload Idle Time Variation Sequencing Constraints
33	2020	**Martinez-Olvera**	Sustainable manufacturing in Industry 4.0	Use an entropy-based formulation to support energy-efficiency analysis in Mass Customization 4.0 environments	Manufacturing Process System Performance Energy & Entropy

By compiling all identified main complexity factors and grouping them according to their similarity, the aim was to detect recurring patterns. These in turn serve as the basis for deriving overarching complexity dimensions that allow the major addressed complexity factors to be systematically characterized. It can be observed that the following five dimensions can be used to group the main complexity factors considered for the assessment of assembly complexity:

Table 4. Dimensions to group the main complexity factors

Complexity Dimension	Focus
Product and design-related complexity	Involves product design, structural dependencies, variant diversity, and system architecture
Process and flow-related complexity	Concerns workflow sequences, assembly planning, task effort, and process interdependencies
Human, organizational, and knowledge-related complexity	Relates to human behavior, skills, communication, and organizational coordination
Time and dynamics-related complexity	Focuses on temporal changes, process fluctuations, and dynamic system behavior
Information and quality-related complexity	Deals with information volume, data uncertainty, entropy, and performance variation

Product-centered approaches for assessing assembly complexity commonly structure models along four main factors (sorted by frequency): product and design-related complexity, process and flow-related complexity, information and quality-related complexity, and human, organizational, and knowledge-related complexity. These categories address physical part characteristics (e.g., size, weight, symmetry), connection properties (e.g., visibility, orientation, fastening types), and system-level architectural aspects (e.g., degree of interconnectivity, centrality, graph energy).

The underlying assessment attributes show substantial overlap. Frequently used dimensions include physical features, handling aspects, connection technologies, and topological indicators.

In terms of application, three primary contexts are evident: assembly planning, quality prediction, and system architecture analysis. Methods are used to evaluate assembly sequences, forecast defects, and assess cyber-physical structures. The assessment frameworks link product design parameters to quality and efficiency metrics.

Information-centered approaches for assessing assembly complexity typically apply a multidimensional framework that distinguishes between the following main complexity factors (sorted by frequency): process and flow-related complexity, product and design-related complexity, and information and quality-related complexity. These categories address the variety and information density of product features and variants, process resources and workflows, execution-related effort, system architecture and modularity, and the degree of uncertainty or choice within configurations.

Recurring attributes include quantitative indicators (e.g., number of parts, variants, operations), diversity measures (e.g., modularity, uniqueness), and entropy-based metrics that capture information content and uncertainty. Physical and cognitive effort is also frequently considered, as are coupling and decomposability. The combination of quantitative and qualitative dimensions enables a comprehensive evaluation of structural and procedural complexity.

Application contexts span assembly and product design, production systems, human-machine interaction, and hybrid or automated systems. Across these domains, the methods aim to support early-stage complexity reduction, bottleneck identification, ergonomic assessment, and system configuration. The overarching objective is to improve quality, efficiency, robustness, or flexibility through informed complexity management. If this is not achieved, the cost implications include rework, delays, and resource inefficiencies.

System-centered approaches for assessing assembly complexity also build on a multidimensional framework that addresses the following main complexity factors (sorted by frequency): process and flow-related complexity, product and design-related complexity, and human, organizational, and knowledge-related complexity. These categories address layout and routing structures, task variability and ergonomic load, mental demands and decision pressure, temporal dynamics such as sequencing and throughput, and entropy-based measures of uncertainty and variant diversity.

Frequently used attributes include connection structures (e.g., nodes, loops, decision points), cognitive load indicators (e.g., information volume, distraction potential), ergonomic factors (e.g., posture, reachability) and temporal metrics (e.g., reaction time, waiting periods). These attributes enable a holistic evaluation of system behavior across structural, cognitive, and dynamic dimensions.

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Application contexts include assembly planning, workstation design, production system layout, mixed-model manufacturing, and smart factory environments. The methods support assessments of workload, error susceptibility, material flow, variant-induced complexity, and real-time responsiveness. The overarching aim is to enhance quality, efficiency, flexibility, and robustness through system-level complexity awareness. If this is not achieved, the cost implications include rework, delays, and resource inefficiencies.

4. Discussion

The structured overview of the different approaches provides insight into their methodological evaluation, with each contributing to the scientific understanding of complexity in manufacturing. This overview also highlights specific implications for current research and opportunities for future method development.

Product-centered approaches: Current research increasingly converges on a standardized tripartite structure (physical part+connections+topology), which facilitates comparability and modular integration into digital tools. As shown in Table 1, new approaches aim to focus on measurable, graph-based indicators and avoid relying on expert opinions. This shift allows complexity to be assessed early in the design phase and supports integration into digital twins. Future methods should build on this modularity to support variant management, platform design, and reconfigurable assembly systems. Cross-domain generalizability remains a key challenge, requiring context-independent complexity definitions and adaptive weighting mechanisms. Moreover, using learning-based systems could help predict further issues and guide preventive actions more effectively.

Information-centered approaches: The scientific foundation of information-centered models is well established, with entropy, diversity, and effort serving as core complexity assessment factors. These models rely on mathematics and are increasingly embedded in digital engineering environments. Future research should focus on enhancing domain-independent applicability through standardized entropy formulations and modular frameworks. Real-time, data-driven complexity evaluation, leveraging live production and design data, represents a critical development path. Additionally, complexity metrics should be directly linked to cost indicators such as rework, delays, and resource efficiency. This is required to increase practical relevance, enable trade-off analyses, and promote strategic optimization of product portfolios and production systems.

System-centered approaches: System-centered models reflect a mature understanding of complexity as a multidimensional and dynamic phenomenon. The integration of structural, cognitive, ergonomic, and temporal dimensions allows for holistic system evaluation. Entropy-based measures are widely used to quantify uncertainty and sequence variability, while human-machine interaction and responsiveness are increasingly considered. Future methods should support adaptive, context-sensitive modeling based on real-time data and learning algorithms. The explicit coupling of complexity metrics with KPIs, such as energy efficiency, error rates, and throughput, will be essential for performance-driven system and cost optimization. Visual decision-support tools (e.g., radar plots, heatmaps) can further enhance interpretability and operational relevance.

5. Summary

This study provides a structured overview and comparative analysis of existing methodologies for assessing assembly complexity in manufacturing contexts. Through a systematic literature review and targeted summary, the paper identifies and organizes a broad spectrum of approaches that differ in their conceptual orientation, application domains, and complexity dimensions. The classification framework developed in this work is based on four core elements: methodological perspective (product-, information-, or system-centered), application context and aim, overarching complexity categories, and specific assessment attributes.

By applying this framework, the study reveals distinct methodological patterns and highlights the diversity of complexity sources considered across the literature. Product-centered approaches emphasize physical and structural product features; information-centered approaches focus on entropy, diversity, and decision effort; and system-centered approaches incorporate dynamic, ergonomic, and cognitive dimensions of production systems. The structured overview enables a clearer understanding of how complexity is conceptualized and operationalized in different contexts.

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The results demonstrate that while numerous methods exist, they are often fragmented and lack a unified classification logic. This hampers comparability and practical applicability, especially in early planning phases where complexity-related costs remain largely undetected. The developed classification scheme addresses this gap by offering a transparent structure for currently existing methods and evaluation. Overall, the paper contributes to the scientific discourse by consolidating existing knowledge, identifying methodological gaps, and providing a foundation for future research.

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