

Technical paper

Handling features in assembly: Integrating manufacturing considerations early in design discussions

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ABSTRACT

The early stages of product design are critical for incorporating manufacturing perspectives. Recognizing the significance of assembly in discrete product manufacturing, the study emphasizes the need to consider the intricacies of assembly early in the design stages. While existing research has addressed assembly features, especially for insertion, this study focuses on handling features, seeking to bridge the gap in their comprehensive representation within the product model. Based on a relational analysis, product characteristics relevant for handling were identified and represented by using a modelling strategy that facilitates their timely addition to the product model. A case study was developed to demonstrate its application. The main contributions of this work comprise an extensive list of product characteristics related to handling processes, a proposal for integrating these characteristics into the product model, and a collaborative way to define product features during product design. Future research directions point to the establishment of a model-based definition for assembly processes, paving the way for enhanced cross-disciplinary communication in the fields of product design and assembly planning.

1. Introduction

Successful product design is a highly cooperative effort involving continuous sharing of ideas, and negotiation between user demands and business objectives. This exchange of thoughts in early concept design needs to include the manufacturing perspective. However, establishing a ‘design-centric’ approach covering all product lifecycle stages and supporting concurrent design and engineering is still challenging [1].

Assembly, an essential process for discrete product manufacturing, provide significant benefits if its particularities are considered early in the design stages. For instance, designing a product considering its assembly method in advance can significantly reduce its manufacturing cost, with an obtainable reduction between 20 % and 40 % estimated in a previous study [2]. It can also influence the cost of the required assembly system [3] and, for automatic assembly, improve the effectiveness of those systems [4]. With tools and techniques continuously developing the design of products and production systems, these benefits remain [5]. Those appealing benefits triggered the appearance of

approaches referred to as design for (automatic) assembly [2,6], assembly-oriented product design [3], or concurrent engineering/design-for-assembly [1], among others.

It is well established that the early introduction of information on product assembly constraints and opportunities in product design delivers competitive advantages [7]. Still, a way to conduct product design by bringing assembly early in the discussions has remained unclear. Moreover, there is a lack of a structured way of integrating production-related properties within the product model. This research aims to promote an early interaction between design and manufacturing, allowing a timely definition of assembly features by defining how these features could be represented within the product information model.

The remaining part of the paper proceeds as follows: Section 2 introduces the influence of product characteristics for assembly, highlights the analysed handling activities (2.4), dives deeper into the research gap (2.5), and clarifies the delimitation and assumptions of this work (2.6). Section 2.6 describes the applied methods, while Section 4 presents the

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proposed assembly features representation and case study results. Finally, Section 5 discusses the implications of those findings, and Section 6 draws conclusions on this work's contributions.

2. Background

2.1. Considering assembly during product design

Design plays a primary role in creating a profitable product design by considering user needs, business goals, and manufacturing capabilities. Choices made during this stage enormously impact the product's final costs and quality, which calls for multidisciplinary analysis and extensive collaboration among different business areas, such as design and manufacturing. To stimulate this collaboration, providing the required tools by utilizing digitalized engineering environments [8] has for decades been essential.

In addition, product design, process design, and process execution, as main phases of product realization, are strongly linked to each other, and therefore, there have been several attempts to integrate them. Specifically concerning product and process design, Lu & Wood [9] remarked that they have been addressed traditionally by two approaches: 'product design for process design' and 'process design for product design', which consider each activity as independent and sequential, in contrast with the concurrent design approach that advocates for simultaneity.

Considering process details early during product design will drastically affect productivity, particularly from the manufacturing and assembly viewpoints [10]. For assembly, suitability of execution [3], labour involvement [11], and costs [12] are also determined at the design stage, which makes feedback to the designer crucial for assembly planning [13]. By separating product design and assembly planning, the information discovered by the assembly planner cannot be fed back to the designer in a way that is both systematic and easy to understand due to the lack of means for information exchange [1].

Furthermore, the advantages of concurrently addressing product design and assembly become more apparent when considering the manufacturing system. Incorporating knowledge about manual, partially, or fully automated assembly systems directly into product design [3] and fostering alignment between design and assembly can considerably influence manufacturing system costs [6]. Von Euler-Chelpin [14] explored the relationship between the product's and the manufacturing system's (as resource) lifecycle, stressing their intersection since a manufacturing resource also becomes a product at some point in the product realization.

Understanding intricate product characteristics beforehand helps determine equipment requirements. Equipment in a manufacturing system can be classified as general-purpose or specialized, either dedicated or non-dedicated [15]. Dedicated specialized equipment, i.e., product-specific equipment and sensitive to a changeover [16], namely tools, could influence and benefit most from early consideration in the product design. This represents a great opportunity, especially for automatic assembly, where the dedicated specialized equipment used at manufacturing culmination consumes most of the manufacturing system design time [17]. For instance, in vibrating bowl feeders, composed of general-purpose (vibratory drive unit) and specialized (bowl, orientation track, feed track, and escapement) components [18], 95 % of the design time is devoted to the specialized components [17], while a single product covers their cost; instead, the general-purpose component, due to its reusability, distributes its cost between several products [19].

2.2. Influence of the physical aspects of a product

Deepening on product design, several authors have described the influence of the product's physical aspect on the production system from different perspectives. This section compiles the physical aspects of a product that appear more frequently in the literature.

Friction has been considered by several authors as a relevant factor in the design of equipment, e.g., feeding tracks and transportation systems [20] since it can affect component stability in gliding or moving tracks [21]. It also influences the force required for gripping [22], increases the insertion forces [23], and can determine the selection of a specific gripping principle for non-rigid parts [24]. At the same time, friction is constrained by the surface characteristics, which can be a decisive factor for gripping surface selection [25]. On the other hand, it can be modified through the application of coatings, considering their influence on impact forces and component behaviour, relevant for feeding systems [26] but also add properties to the surface that can be taken advantage of by gripping systems [27].

Concerning the component material, it is important to understand its role as a component constituent and as an interacting factor. As a component constituent, its physical and chemical properties assist in the handling equipment selection. For instance, strength and rigidity can determine the direction and magnitude of gripping forces required [25]; modulus of elasticity and shape structure make the distinction between rigid, flexible or elastic components with their corresponding challenges [28]; magnetic permeability makes a component right for certain types of feeders [10]; while electrical conductivity and air permeability [27] can restrict the use of gripping principles. Considering the interaction between the component material and equipment material can affect not only friction forces but also component alignment [29], and clamping system selection [30]. Moreover, when considering the surroundings, material properties that can vary according to the conditions of the surroundings, as in the case of non-rigid materials [24] impact on the gripping mechanism applicable, or material phase changes induced by external conditions need to be considered in the fixture design [31]. More details on the influence of environmental conditions over the gripper design is described in a good way by Riley [27]. Finally, material selection determines prominently the final product mass and consequently the weight, which impact the grasping, controlling, and moving time [10].

Geometric shape is the physical aspect that provides the most information quantity enabling design for assembly [8] and significantly influencing the requirements for handling specialized equipment. For instance, a successful shape interaction between the product and bowl/track boosts the functionality of automatic feeders [32], narrows the force-applying possibilities for grippers [33], and determines the mechanical strategy to orient the components in all handling tasks [10, 12, 34].

Component geometry has also been deemed relevant to reducing alignment errors in feeding by the design for assembly (DFA) studies [35]. Its straightforward characterisation, i.e., classifying the products according to their overall shape as prismatic, cylindrical, or headed components, has been used to preliminary select an automated handling device [36]. Additionally, it is the product characteristic that determines if a component requires an assembly direction different from above [10], or if it is prone to tangle, nest, or jam [35].

Another relevant characteristic derived from the component geometry is symmetry. Authors have established several kinds of symmetries for a part, the rotational symmetry being the most cited. In feeding, this type of symmetry aids in filtering acceptable orientations [32]. Boot-hroyd [10] appointed alpha and beta symmetries in his studies: alpha symmetry, evaluating the component rotation about an axis perpendicular to its insertion axis; and beta symmetry, its rotation about the insertion axis. Even when a symmetrical design facilitates component handling, including physical asymmetry or non-functional shape features can ease its orientation when a specific detail needs to be visible [37].

Although geometry and symmetry are typically associated with the external shape of a component, internal features are often overlooked. These features, present in a significant share of produced components [38], can aid component orientation and location. However, it is critical to weigh their pertinence to their cost implications [37]. As with the

external features, certain types of symmetries have been established for internal features: cyclic (or rotational) symmetry, when the features repeat every specific number of degrees around an axis, and mirror symmetry, when they reflect about a plane. Its combination forms a third type of symmetry, namely point symmetry. An additional type of symmetry, gamma symmetry, was proposed to evaluate the component symmetry about the insertion axis (beta symmetry) considering the internal features [38]. Besides, the size and shape of internal features can determine their stacking capabilities and help in defining guides for handling systems. More information on internal features can be found in [38].

The above-mentioned aspects are a share of the multiple product characteristics that can influence and give constraints and opportunities for feeding, fixturing, and grasping tasks. Their study has grown enormously from the natural resting aspects [39], i.e., the probabilities of how "a part can rest on a horizontal surface" [10], for sensorless systems [40,41], the understanding of the role of the geometry and symmetry to achieve stable orientations [16], the position of the centre of mass in the direction of rotation [42], to the identification of the challenges of handling non-rigid components [27]. Gradually, assembly aspects were included in the discussion, e.g., the influence of the assembly sequence to determine the surfaces available for grasping and fixturing [43,44]. Then, the need to make explicit the link between the product characteristics and the different manufacturing processes was strengthened, assembly not being an exception.

2.3. Handling features in assembly

Assembly features were characterized as carriers of assembly-related (technological, functional, geometrical) information in a previous work [45]. While these features are relevant technical elements during product design [4], their definition and classification remain vague. Therefore, this work started by exploring Boothroyd's hypothesis on handling as a critical issue for automatic assembly [2].

A brief literature review revealed an extensive list of assembly feature types (available in Appendix A). Within these types, three stood out: insertion, handling and positioning. Although the boundaries of positioning features remain fuzzy, there is a clear distinction between insertion and handling. Insertion features focused on mating relationships between components and were referred to as connection, joining, or mounting [46]. Conversely, handling features considered mostly the individual component characteristics and included grasping, feeding, fixturing, manipulation, gripping, and placing as subcategories [10, 47–49]. Despite research efforts, studies tackling handling features have been under-investigated and fragmented due to the separate analysis of specific tasks. The impact of handling features on the assembly process and product design needs to be further studied, particularly in the lack of attention that has been given to their representation in the product model. Thus, this work focuses on the handling features, aiming to contribute to their timely identification and representation from the early stages of product design.

Material handling is a topic of interest in several fields, addressed with different levels of granularity, from logistics and transport to specific processes, such as assembly. In the context of assembly, Redford [36] outlined the requirements of material handling from the handling of the components into the systems to their transport out of the assembly cell. More recently, Neb [28] narrowed the definition of handling to the impact of the joining part, with its efficacy determined by whether it is practical or cumbersome to the process. The latter notion of handling features, restricted to the assembly domain, is the one adopted in this work to avoid overlapping with concepts out of the manufacturing scope.

Among all the elements of the handling system (environment, handling device, part, task, and gripper) [50], the part, especially its design, was identified as key to enhancing the efficiency of the assembly process and enabling its automation [3,10]. Therefore, a thorough

analysis of the types of handling features could aid in understanding their particularities and relation with the component design. Although several classifications of handling features have been proposed (e.g., feeding and orienting [10]; feeding, fixturing, and grasping [47]; and forbidden, restricted, and grasping [44]), this work focused on the three most frequently cited types of handling features for automatic assembly according to the results of the review in Appendix A: feeding, fixturing, grasping, and its sub-types, depicted in Fig. 1.

Feeding a part, according to [51], comprises three stages: separation, orientation and presentation. Separation, also referred to as singulation [42], implies isolating a component from a group [51]. Orientation consists of a combination of rotation [38,51] and alignment movements [10]. Hansson used structuring to include separation and orientation under a single stage [52]. Then, presentation implies transferring the components after structuring [51,52], linking the feeder to the rest of the production system [31]. Besides, if magazines are employed, piling components in a specific orientation is referred to as stacking [38]. Product characteristics to pay attention to for automatic feeding are geometric information [53], required orientation, symmetry and characteristics of sensorless manipulation [41], as well as product shapes prone to tangling, nesting and jamming.

Fixturing involves securing the position and orientation of a component or assembly during the execution of a process, withstanding the forces that might appear [32]. It also considers how the components can hold themselves together [54]. Bi and Zhang [55] pointed out three sub-functions of fixturing: locating, supporting and clamping. Locating concerns for positioning the object in the space by restricting unnecessary degrees of freedom [54]. After that, the component is held against locators and supports to keep its position and resist any applied forces, which is known as clamping [56]. If the component is prone to deformation, supports can be included to help minimize its effects during the process (supporting) [54]. From the product design perspective, fixturing is interested in characteristics related to stability [55], dimensions, orientation, weight, stiffness and material properties of the component, type, condition and availability of the surface, approaching direction, interferences, clamping force, orienting requirements [30,56]. Also, operations sequence [57], datum reference frames and geometric adaptability of the fixture to the product shape are essential for clamping points definition [30]. For non-rigid components, additional considerations should be made, such as inter-layer retention forces, ply separation and order retention [24].

Grasping can be defined as bringing a component into contact with a device that restricts the component movement by mechanical means independent of gravity or other forces [58]. This definition implies movement, not a static positioning of the device on the component, usually understood as gripping [43]. In fact, according to Fantoni [27], seven stages compose grasping: approaching, coming into contact, increasing the force, securing the object, moving or processing, releasing, and monitoring; the latter being executed throughout the entire process. This work addresses the first two stages as reaching, similar to [58], while gripping will cover the next two stages to differentiate the terms found in the literature. It is worth noticing that, after gripping, the component and the device (gripper) will move together, creating another temporal assembly. Several product characteristics become relevant for this task. Geometry, size, material, weight, and surface condition are among the authors most cited characteristics [25, 27,33,44,59–61]. Other examples are: applied forces and delicateness [33]; contact site [50]; flexibility, sensitiveness to scratches and pressure, permeability, and torque [27]; hardness, coatings [44]; component accessibility, suitable gripping surfaces, and fragility [8], pairs of parallel and opposing surfaces, centre of mass, type of surfaces, and number of components [25]; and, thickness, flexibility and permeability, among other, for non-rigid components [24].

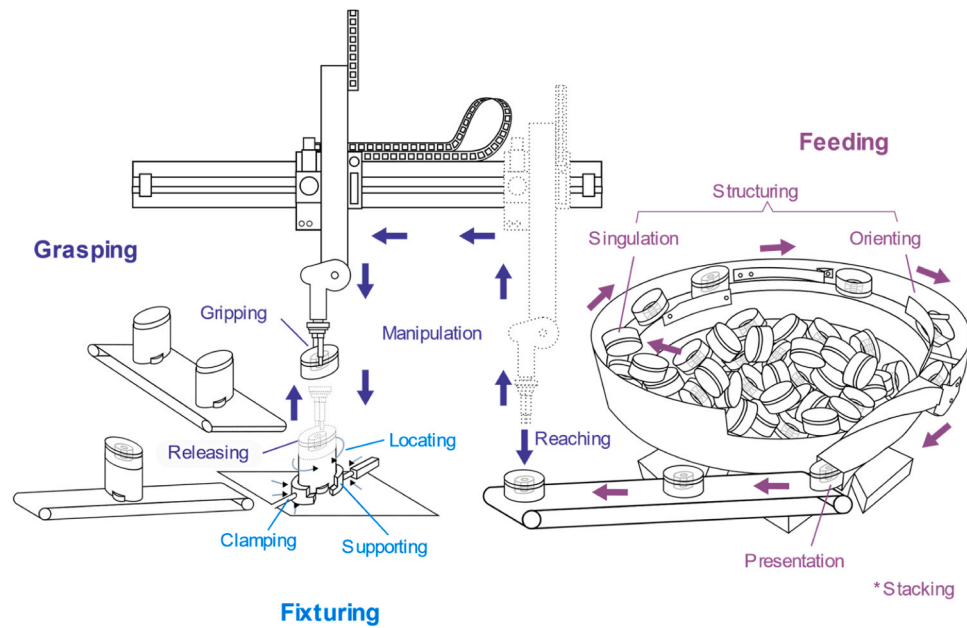


Fig. 1. Handling features in automatic assembly.

2.4. Existing methods

Several attempts have been made to incorporate assembly aspects in the product design, from traditional checklists and product coding systems to robust feature recognition approaches.

Traditional aids for assembly-oriented product design were compiled by Bäßler [3], together with selection method and implementation guidelines.

Regarding coding systems, the DFA (Design for Assembly) approaches, assigned a code based on how easy it was to manipulate a component depending on its geometry and physical characteristics. DFA inspired computer based part coding methods: among them the notable Automatic Handling Part Coder (AHPC) [12] with a focus on handling. In the domain of manual assembly, the methods are based on time penalty [2], scores [62], or hybrid. In the automatic assembly the methods are based on coefficients for the machine cost (investment is the main cost here... not time (salary) [2] or scores [6]. On the other hand, assembly-oriented product design systems such as DEMOS (Design and Modelling System) [4], and FANTASY (Feedback Assembly Integrated Autoredesign System) [1] made attempts to include different aspects of assembly systematically along the design process. More recently, assembly features recognition systems were proposed, for instance, based on 3D computer-aided design (CAD) models [28], by creating liaisons for representing assembly structures [63], or by using an ontology [64].

Other efforts highlighting the need for integrating assembly information from the design stages can be found in the literature, such as the one proposed by Rodríguez-Toro [7], which proposes the integration of product complexity metrics with design evaluation tools. Also considering product complexity, Samy and Elmaraghy proposed attribute matrices scoring handling and insertion complexity [65] and later assessed the influence of those attributes and product variety in the assembly system complexity [66]. Rampersad [67] also advocated to include assembly in the product design process and exposed the connection between the product characteristics, the assembly processes and the production system elements.

Finally, significant works targeting handling tasks have been proposed in recent years by [28], with the FfA (Fitness for Automation) approach; [68] with the assembly features-based model for assembly planning; and [44] with a method to identify constraints for grasping planning from the product manufacturing information.

Yet, as pointed out by Chaimae et al. [69], these approaches primarily target the detailed design stage, limiting their impact on the product design, even worse when the deficiencies of the current product models identified by Net [70] are still valid, e.g., use of problematic modelling primitives, dissimilar representation and process descriptions, inequitable attention to geometric and functional representation.

Seeking to overcome the difficulties mentioned above, international organizations have pushed for adopting standardized product models. The Initial Graphics Exchange Specifications (IGES) was the first neutral format for the exchange of geometric shape models between several platforms, enabling transfer of surface and solid models [71]. Still, its functionality is limited since product manufacturing information is not included in the format [72]. Although it was discontinued, few companies still use it. A more recent proposal is the JT (Jupiter Tessellation) format, defined in the ISO 14306:2017 standard, which has visualization capabilities, including product manufacturing information, resulting in industrial adoption [73]. However, its limited coverage of product lifecycle information, weak version compatibility and problematic dependencies on proprietary shape calculation algorithms, are severe shortcomings.

ISO 10303 or STEP (STandard for the Exchange of Product data) is an effective CAD data exchange standard [71] capable of representing geometry and semantic product manufacturing information (PMI) [73] along the entire product lifecycle stages [74], and readable by most CAD platforms [75]. STEP standard has a modular structure consisting of integrated resources (IR) and application modules (AM) which are used as constructs to compose application protocols (AP) [76]. Some of the most relevant parts are, AP242 - Managed Model Based 3D Engineering [77], AP239 - Product Life Cycle Support [78], Fundamentals of Product Description and Support (IR) [79], and Generic material aspects (AM) [80], to cite a few. Additionally, to support the implementation and testing of the STEP AP242 standard, the Computer-Aided-"x" Implementor Forum (CAX-IF) gathers CAX system developers and provides recommended practices to establish a common ground for the different commercially available CAD systems. For instance, there are recommended practices for the representation and presentation of PMI [81], user-defined attributes [82], composite materials [83], and PMI Unicode string specifications [84].

2.5. Research gap

Summing up, the literature on the inclusion of assembly knowledge into product design has highlighted a persistent need for systematic methods and collaboration strategies for facilitating cross-disciplinary work in this area. Also, it is clear from different authors’ claims that the earliest this collaboration happens, the better the outcomes on the overall product realization.

In particular, in the domain of automatic assembly, a very time consuming activity is the design of dedicated specialized equipment. This task consists of integrating general equipment and heavy machinery with specifically design tools for the handling and insertion of the product components. With reference to the handling of the component, typical processes involve use of gripping, fixturing, and feeding devices. Considering the work of von Euler-Chelpin [15] regarding the intersection between the product and the manufacturing system lifecycles, and digging into the equipment composing the manufacturing system, in the case of automatic assembly, it is noticeable that product design dictates the requirements for the design of such dedicated specialized equipment (see Fig. 2). Such requirements are today not explicitly mentioned into de the product designed and are usually inferred from the final design by the production system integrators. This means that often, a reflection about how to efficiently implement these requirements is made only when the product is no longer in the design phase. In view of this, if the collaboration between product design and assembly planning begins earlier than the production/use stage, the aforementioned requirements can be established and made available during the product design phase. Focusing on the handling phase of the automatic assembly can provide a great opportunity for accelerating the development of grippers, fixtures, and feeders, since specific details of the product about automatic handling will be considered from the very design of the product, allowing the design of those dedicated equipment to start in advance.

In practice, a few shortcomings can be identified in the research up to now:

- Typically, DFA and coding systems are applied once the detailed product design is completed, and regrettably, the meaning of such

codes or indexes is not carried throughout the entire product realization. These evaluations are made without the designer, making it difficult to understand the impact of design decisions on product manufacturing due to a lack of knowledge in this area [8].

- The importance of communicating the design intent along the whole product realization continues to be overlooked, resulting in feature recognition systems frequently re-creating information already assessed during product design [85].
- There is no space where people from design and manufacturing can interact and express their ideas during early product design, reach a consensus, and portray their decisions in the final design.
- Considering that the assembly process is composed of handling and insertion tasks, it can be noticed that most existing works focused solely on the insertion and mating aspects of assembly, addressing mostly manual assembly. Disregarding the handling and presentation of assembly components reduces the application of those approaches in automatic assembly where these are essential tasks.

Overall, which aspects of the product design need to be considered for facilitating automatic handling and assembly are still open questions. Therefore, this research aspires to fill the gap in the representation of handling features for automatic assembly, providing a mechanism to include manufacturing information in the early product design.

To the best of the authors’ knowledge, this is the first comprehensive approach to integrate product characteristics (beyond geometric dimensioning and tolerancing) influencing handling processes directly into the product model. Further, it seeks to provide a structured representation adaptable to different data types by leveraging the capabilities of existing international standards for product information exchange, enabling future automatic extraction and interoperability.

This synthesized information could provide practical inputs to product realization stakeholders. Having readily accessible information and initial identification of product characteristics related to assembly equipment functions could enable an early kick-off of special tools and equipment design, seeking to convert the design of products and resources into parallel activities [11,66,86].

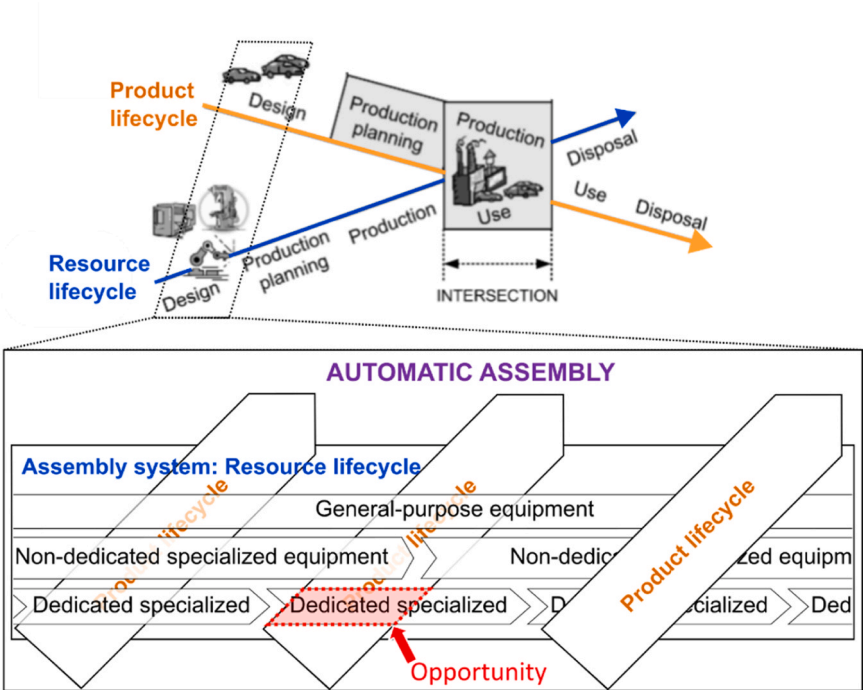


Fig. 2. Scope of the current study considering the work of [14].

2.6. Delimitations and assumptions

A foundation of this research was the concept of intelligent products, according to which the product communicates with its environment, stores its data, and dictates its production requirements [87]. Building upon this concept, the authors considered a product able to determine its optimal assembly requirements, i.e., this work considered the product perspective and how its characteristics defined in the early design stages determine its manufacture. Adding this information to the product model only enriches and supports the equipment manufacturer’s decision-making.

Regarding the production system, this work considered a scenario composed of general-purpose equipment flexible enough to accommodate any dedicated specialized tool necessitated by the product due to its design, i.e., the tool specifications are defined by the product. Different scenarios where specific tools and their specifications are known (e.g. [88]) can be addressed using more suitable methods.

This work focused on handling features within the domain of automatic assembly for mechanical products, as described in Section 2.3. The developed analysis comprised relevant literature on the relationship between product characteristics and handling tasks.

Based on the aim of this study, publications presenting assembly sequencing and line balancing procedures, assembly sequence optimization methods, purely geometrical feature recognition algorithms, business-related indicators, economic factors, or productivity requirements were not considered in the examined literature.

Additionally, the proposed model reflects the product modelling standards available at the time of its conceptualization.

3. Methods

This research intends to determine which criteria relevant to automatic assembly, especially handling, are established during early product design stages and how they can be represented synthetically within the product model. To these aims, this study used a mixed methodology. It started by applying relational content analysis of relevant literature to identify the relevant concepts and their relationships, continued by proposing a strategy to represent the found concepts within an information model and finished by illustrating the proposed model in a case study, as summarized in Fig. 3.

3.1. Relational analysis

Relational analysis is a type of content analysis particularly useful

when exploring semantic relationships between concepts, enabling the gathered data to be used in quantitative and qualitative operations [89, 90]. In this study, the steps for implementing the relational analysis were inspired by Busch et al. [90] and described below. It’s worth noting that all information processing was conducted manually.

3.1.1. Select the body of knowledge

A previous work of the authors identified "assembly features" as the most commonly used term to describe the group of product characteristics of interest during the assembly process design or planning [45]. Therefore, in this investigation, the primary sources of information were relevant academic and non-academic publications addressing assembly features, design for (automatic) assembly, and assembly automation. Emphasis was placed on articles addressing the relationship between product characteristics and assembly activities on feeding, fixturing, and grasping, as noted in Section 2.3. Further, the perspective of the product designer (to identify product information essential for the design process), the assembly or production planner (to determine product characteristics required for resource selection), and the equipment designer (to understand product inputs needed to start the equipment design process) were considered. Further details are listed in Table 1.

Table 1
Specifics on collection of body of knowledge.

Data collection	
Sources	Academic and non-academic publications on assembly features, assembly automation, and design for (automatic) assembly, published in 1968 –2023.
Keywords	"assembly features", "design for automatic assembly", "assembly automation", "product characteristics for assembly", "feeding", "fixturing", and "grasping"
Databases	Scopus, Google scholar
Initial corpus:	97 papers.
Screening and selection	
Inclusion criteria	Papers discussing product characteristics related to feeding, fixturing, or grasping in automatic assembly, from the perspectives of product design, assembly planning and equipment design.
Exclusion criteria	Papers focusing solely on manual assembly, assembly line balancing, assembly sequencing, automatic feature recognition, studies examining assembly from the dynamic, economic, kinematic, and operating principles perspectives.
Final corpus:	60 papers

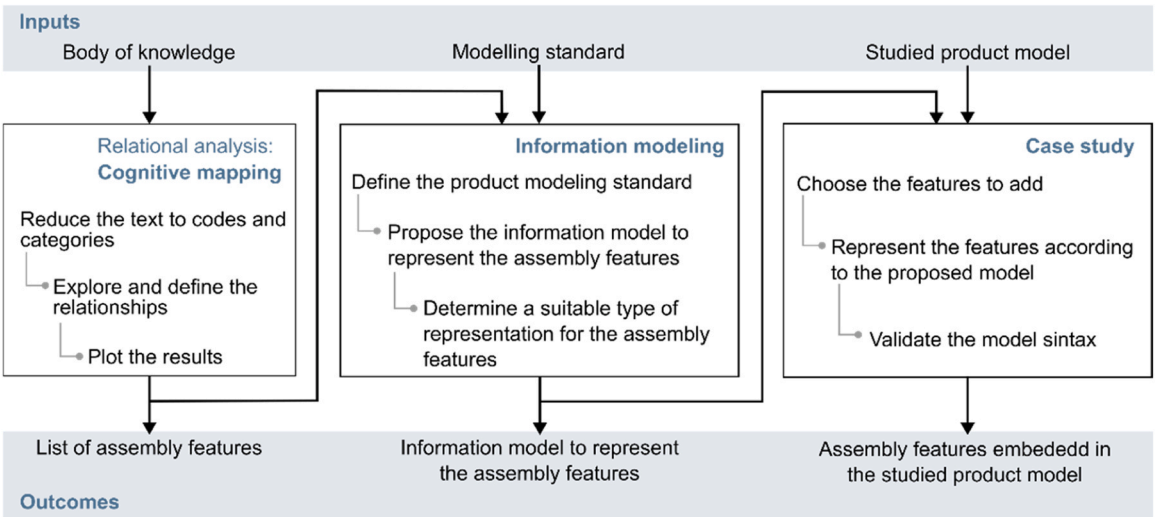


Fig. 3. Summarized methods.

3.1.2. Choose the type of analysis

Based on the aim of the study, cognitive mapping was selected as the primary relational analysis method. Since this method aids in understanding not only concepts but the relationships between them [89], it facilitates identifying the relevant product characteristics related to automatic handling and how they influenced each other.

3.1.3. Reduce the text to categories and code for words or patterns

Focusing on detecting the product characteristics (concepts) related to handling, the most relevant types of these features (feeding, grasping, and fixturing) were used as categories. Also, inspired by the aspects and the conditions for identifying feasible subassemblies proposed by [91], six subcategories were defined. These subcategories allowed an extensive coverage of the handling features from different perspectives.

Having established the categories and subcategories, all product characteristics, hereinafter concepts, were extracted from the body of knowledge. This first set of concepts was cleaned to avoid having semantically duplicated, overlapping, or homonymous concepts (Table 2).

Finally, the categorized concepts and their respective sources were summarized in a concept matrix.

3.1.4. Explore and code the relationships

Taking advantage of cognitive mapping's capability of revealing relationships between concepts, this step focused on determining how the previously extracted concepts were linked to each other and their assigned category.

With this aim, each concept was analysed to explore a physical variable, property, or parameter used to derive it (e.g., an object's mass can be derived from its volume and density). Finally, the concepts sharing a physical variable, property or parameter, directly or indirectly, were linked, establishing a network of interconnected concepts.

After identifying the concepts and their relationships, they were classified based on the type of information they represent and their potential linkage to the product structure. In this work, three hierarchical levels were considered for the product structure: the product level being the highest, a component (or subassembly) level in the middle, and the geometry level the lowest. This process is summarised in Table 3.

3.1.5. Plot the results

The concepts and their relationships were mapped independently for each category, according to the corresponding product level and showing the type of information they represent (functional, technological, or geometrical dimensioning and tolerancing (GD&T)). These mappings synthesized the product data into information for handling

Table 2
Specifics on categorization and coding.

Categorization framework	
Main categories	Feeding, grasping, fixturing.
Subcategories	Accessibility, stability, process constraints, manipulability, positioning efficiency, nature of the component.
Concept extraction and coding	
Coding criteria	Authorial usage, contextual presentation, intended meaning.
Process	• Read each source and extract product characteristics related to handling • Assign each characteristic to a category and subcategory according to the coding criteria. • Record the coded concepts with its respective source.
Concept count:	128 concepts
Data cleaning	
Process	• Identify and merge semantically duplicated concepts (e.g., "surface finish" and "surface condition"). • Resolve homonyms by adding context (e.g., "force" for clamping vs. "force" for gripping vs. "force" for retention).
Unique concept count:	106 unique concepts

Table 3
Specifics on exploring the relationships.

Relationships mapping	
Relation criteria	Share physical variables, properties or parameters
Process	• For each concept, identify a potential relation to other concept based on the established criteria • Record this relationship by visually linking both concepts through the identified variable/property/parameter
Final concept count:	89 concepts
Hierarchical classification	
Types of information	Functional (for the user, for the assembly system), Technological, or GD&T
Product structure level	Product: global, general characteristics affecting the product as a unit. Component: characteristics affecting only a part or subassembly. Geometry: characteristics affecting a specific portion of a component.
Process	• Classify each concept based on its corresponding information type. • Assign each concept to a specific product structure level according to its degree of influence on the product.

tasks in automatic assembly.

The relational analysis yielded a list of product information deemed beneficial for assembly process planning, particularly during handling tasks. The elements of this list, grouped into the three main categories, comprise the handling features.

3.2. Information modelling

Several product modelling approaches and academic works were explored to represent the features identified in the relational analysis. After consideration, the ISO 10303 standards family (STEP) was selected based on its capability to handle product data along the entire product lifecycle [74,76], its human and machine readable information structure (not binary or encrypted), its ability to provide a complete geometric shape representation of the product together with process-relevant information [73], its information model flexibility compared to the other available product data standards, its potential for developing model-based enterprise solutions by combining semantic and geometrical product information [75], its data exchange capabilities as a neutral CAD format [71], and its broad dissemination in the manufacturing field.

To assess the usability of STEP in representing the identified concepts, several parts of the standard were studied, focussing on the Application Protocol 242, its respective application modules, integrated resources, and recommended practices. Based on this study, a strategy to include handling-related information within the product model described by STEP was proposed. This proposal considered the hierarchical product structure inherent in the STEP product model.

Later, an examination was conducted to determine the extent of coverage for the identified concepts within STEP. For concepts not already modelled, suitable representation types were determined. Finally, these concepts were integrated into the STEP product model using the proposed approach.

The resulting model aimed to expose the relationships between the component (geometrical or non-geometrical) characteristics and the handling processes, by making them explicit and easily identifiable.

3.3. Case study description

As a final step, an illustrative case study [92], was developed to show the application of the proposed model to an existing product.

Considering the focus of this research, several criteria guided the product selection for the case study. First, the product needed to be a mechanical component produced through automatic assembly,

according to the scope of this study. Second, it should be a multiple-part product with a low- to mid-complexity assembly sequence to avoid highly specialized assembly processes. Third, to demonstrate the easy implementation of the method, products with publicly available 3D models were prioritized. Finally, to promote the generalization of the results, the ideal product would have a reasonably common geometry, simple operation, high market availability and applicability across several industries. Therefore, a simplified pneumatic cylinder whose CAD model was publicly available in an assembly repository [93] was used. Based on this product, the case study protocol according to [94] (Table 4) was followed.

4. Results

Since the focus of this work is the representation of handling features for automatic assembly, this section presents the results obtained from the application of the methods described in Section 2.6, emphasizing the proposed approach for including this information in the product model. This section starts by presenting the results of the relational analysis, followed by the description of the proposed model, and concludes with the outcomes of the case study.

4.1. Results from the relational analysis

To extract the relevant concepts and explore their semantic relationships, a four-step relational analysis was performed according to

Table 4
Case study protocol.

Case study scope and objectives	
Purpose	Explore the feasibility of enriching the CAD model with information regarding the identified handling features.
Subject	Pneumatic cylinder assembly taken from [93], consisting of five components excluding mechanical fasteners and seals (Fig. 4).
Case study structure	
Areas of focus	Representation of feeding, fixturing, and grasping features, as defined in Section 2.3.
Research framework	Handling features for automatic assembly (see Section 2.3)
Research stages	1. Data collection 2. Data analysis 3. Model implementation 4. Validation.
Data collection	
Data sources	Internal: Technical documentation of commercially available pneumatic cylinders from different OEMs available in the vendor website, catalogues, and technical specifications. External: Documentation of the selected standard from national and international standardizing organizations, and recommended practices from relevant implementors forum.
Supplemental data	Academic works regarding assembly features and product information modelling.
Outcomes	1. Product information of the case study's subject. 2. List of relevant handling features to represent. 3. Product model enriched with the previously identified handling features. 4. Validated product model including handling features.
Analytical procedures	
Process	• Collect the data from internal and external sources. • Select the handling features to add to the different assembly components based on their frequency of use, diverse nature, and value ^a for the handling tasks assembly. • Represent the product (geometrical) model in the selected standard. • Add the handling features by applying the proposed approach to the product model. • Validate the compliance with the standard selected in Section 3.2, by using an external tool in line with such standard.

^a Value in this work is measured by how many types of handling features require the information provided by the concept, how straightforward is its use by production planning, and how rare it is to find this information available in current product models.

the methodology described in Section 3.1.

4.1.1. Body of knowledge

In the first stage, relevant publications addressing handling features were gathered from academic and non-academic sources to constitute the body of knowledge. This study included 97 publications between 1968 and 2023.

Concerning the proposed categories (feeding, fixturing, and grasping), their chronological order of appearance was possible to identify. Feeding-related topics such as the natural resting aspects of a product and their influence on automatic feeder design and selection received increased attention until the early 2000s, first as sensorless automation approaches and later dealing with the active role of robots in parts feeding. From the 2000s, the papers included automation technologies for this process. Regarding fixturing, publications followed a similar trend as feeding, i.e., starting as merely mechanical approaches, going to the design of modular and flexible systems, and continuing with automated fixturing methods. Nonetheless, fixturing has been studied not only for its role in assembly but also for supporting machining operations, so it can be assumed that their development started long before the timeframe of the current study. As for grasping, its study went on with the development of robotic grippers, always in parallel with the analysis of the human grasping methods. Some publications targeting automatic feeding also addressed grasping when including industrial robots in the analysis. Growing attention was observed in the last decade tied to the development of innovative robotic grippers and gripping principles.

4.1.2. Extracting concepts and categories

From the body of knowledge built in the previous stage, the product characteristics (referred to as concepts in this study) in the context of the handling subprocesses (fixturing, feeding, and grasping; referred to as categories) were extracted, coded and cleaned. A total of 106 concepts were identified. Table 5 shows an excerpt of the concept matrix and the context in which each concept appeared; a complete table is available in Appendix B.

Some considerations were derived from this concept matrix:

- Authors considered diverse types of concepts. Both, qualitative and quantitative concepts can be found between the most cited ones: shape, size, weight/mass, and materials.
- Numerous concepts were applicable not only in one category. Even when some concepts were used for a specific category, others were employed in two of the three categories, and many others were pointed out in the broader context of handling, which covers feeding, fixturing, and grasping.
- Several concepts were mentioned by different authors using synonyms, homonyms, overlapping, or only partial concepts.
- Some concepts needed to be understood in its extended context to be linked to a specific category. For instance, few publications use the expression fixing a component in the sense of adjusting its position, in contrast with the sense of preventing its movement.
- Several authors also considered key performance indicators and production rate requirements, especially for the design of equipment for the three categories. However, only product characteristics in the form of geometrical, functional, and technological information were considered in this work.

4.1.3. Exploring and mapping concept relationships and plotting the results

The previously extracted concepts were further examined to identify derived concepts and reduce them to one representing the entire class (Table 6).

All resulting concepts were arranged according to their corresponding handling feature category (feeding, fixturing, or grasping) and subcategory, as seen in Fig. 5. Concepts used in all three categories

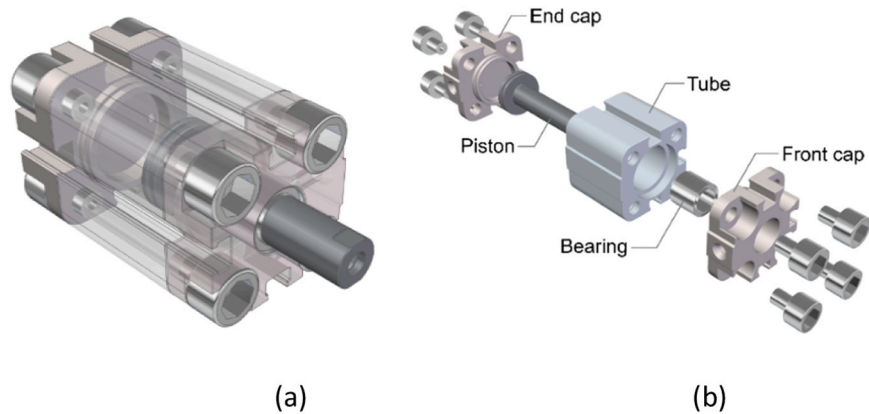


Fig. 4. Pneumatic cylinder used as case study (a) Assembly, (b) exploded view.

Table 5
Excerpt of the concept matrix featuring the 20 most cited concepts and the sources contributing the higher number of concepts. In the table, F= feeding, G= grasping, X = fixturing, H=handling in general.

Source Concept	Total sources per concept	[10]	[6]	[27]	[91]	[30]	[70]	[65,66]	[24]	[61]	[60]	[25]	[67]	[95]
Total concepts per source		49	23	23	15	15	14	14	14	14	13	12	11	11
Shape	25	F	F	G		X	G		G	G		G		
Size	20	F		G	F, G	X	G	F, T			H			H
Weight/mass	18	F	H	G	F, G	X	G			G	H	G	G	H
Materials	12					X	G		G	G		G	G	
Centre of mass	11		F, G		X							G	G	
Tangling	11	F, H	F	G	F, G			F			H		F	G, H
Fragility	10	F	F	G	F, G	X		T		G				
Flexibility	10	F, H	G	G	F, G			F, T	F, X, G					G
Symmetry	9	F, H	H		F, G						H		F	
Nesting	8	F	F	G				F			H		F	G, H
Alpha symmetry	7	F	H					F			H			H
Beta symmetry	7	F	H					F			H			H
Delicateness	7	H		F, G				F						G
Friction	7		F	G										
Natural resting aspects	7	F	F				G							
Surface accessibility	6					X	G					G		
Marked polarity	6	H			F, G								F	
Length	6	H	F, X, G			X								
Overlapping	6	F										G	F	
Surface condition	5		F		G	X	G		G					

Table 6
Reduced concepts for simplification purposes.

Reduced concepts	Representative concept
Alpha symmetry, beta symmetry, 180° symmetry about axis	Symmetry
Point symmetry, rotational symmetry, end-to-end symmetry	
Cylindrical shape, spherical, disc-shaped, U-shaped, tubular parts, cup-shaped parts, prismatic parts, polygonal objects, truncated cone-shaped parts, headed parts	Shape
Internal features symmetry (gamma, cyclic, mirror symmetry), size and shape of internal features, location of internal features	Internal features

(common concepts) were depicted in the centre.

Closer inspection of the concept arrangement showed a significant overlap between feeding- and grasping-related concepts, as did fixturing and grasping, suggesting a strong connection between them. However, fixturing and feeding did not share any specific concept besides the ones common for the three categories. It is also apparent that the grasping category can take advantage of a substantial number of concepts.

To expose the relationships between the concepts, they were mapped for each category (Fig. 6 for feeding, Fig. 7 for fixturing, and Fig. 8 for

grasping), taking into consideration the product structure and type of information they communicate.

From the mappings, some points need to be highlighted:

- Depending on the concept and the category, the level of detail required for its description varied.
 - o Size, for instance, was mentioned by several authors in terms of the diameter and length of cylindrical components, and the length, width, and thickness of prismatic. Other authors advocated for the bounding box for all product shapes, while for others, the overall length of the component was enough.
 - o Shape is another example. For feeding tasks, a simple representation might be enough for defining the type of device to use while for grasping and fixturing, a more detailed description is required, ranging from available surfaces to specific points and surface curvature.
 - o Required material properties differed significantly, for instance, from feeding to grasping. While for feeding, mainly mechanical properties were considered, for grasping, mechanical, electrical, and even chemical properties are relevant due to the variety of grasping principles.



Fig. 5. Concepts coloured by purpose and grouped in categories.

- Due to their variety, several concepts can be quantitatively estimated, while others had a qualitative estimation or were reduced to specific classes to facilitate their management. This consideration is decisive for the modelling stage.
 - o For instance, some material properties were described through the values or ranges of their corresponding parameters, e.g., density, elastic module to describe elasticity, and electrical conductivity for conductive materials, among others.
 - o In contrast, shape characteristics were reduced to qualitative expressions depending on the task, as mentioned before, or a few geometrical elements or descriptions of certain regions provided enough information for the analysed subprocess; a comprehensive product shape description was hardly needed.
- The product alone cannot entirely define some concepts.
 - o Friction is the most apparent concept in this case. The interaction between materials defines the friction coefficient, i.e., prior knowledge of the product and production system building material is required.
 - o In feeding, the concept of shape interaction appeared in the sense that the shape of the bowl/track and the product shape together can influence the system functionality.
- Several concepts are pertinent to specific tasks or specific product types.

- o Base part and assembly complexity are meaningful concepts for fixturing since they enable the identification of the components to be fixed and the areas available for that purpose, but that can be disregarded for other tasks.
- o Order retention and ply separation are concepts required when handling piled components, or large flat objects (plies), accordingly.

In summary, the mappings revealed a complex relationship between concepts in the same category, which varies depending on the category. In the same manner, some concepts and priorities changed when planning the handling tasks. Nonetheless, the number of common concepts is extensive.

4.2. Proposed model

Based on the retrieved concepts and their relationships, a way to integrate this information into the product information model was investigated.

In this work, the product information model followed the Application Protocol 242 of the ISO 10303 standard [77] (as defined in Section 3.2), which can use the application modules and integrated resource constructs available in the STEP family, as described in Section 2.4. Based on the modelling constructs in those resources and the recommended practices of the Computer-Aided-"x" Implementor Forum

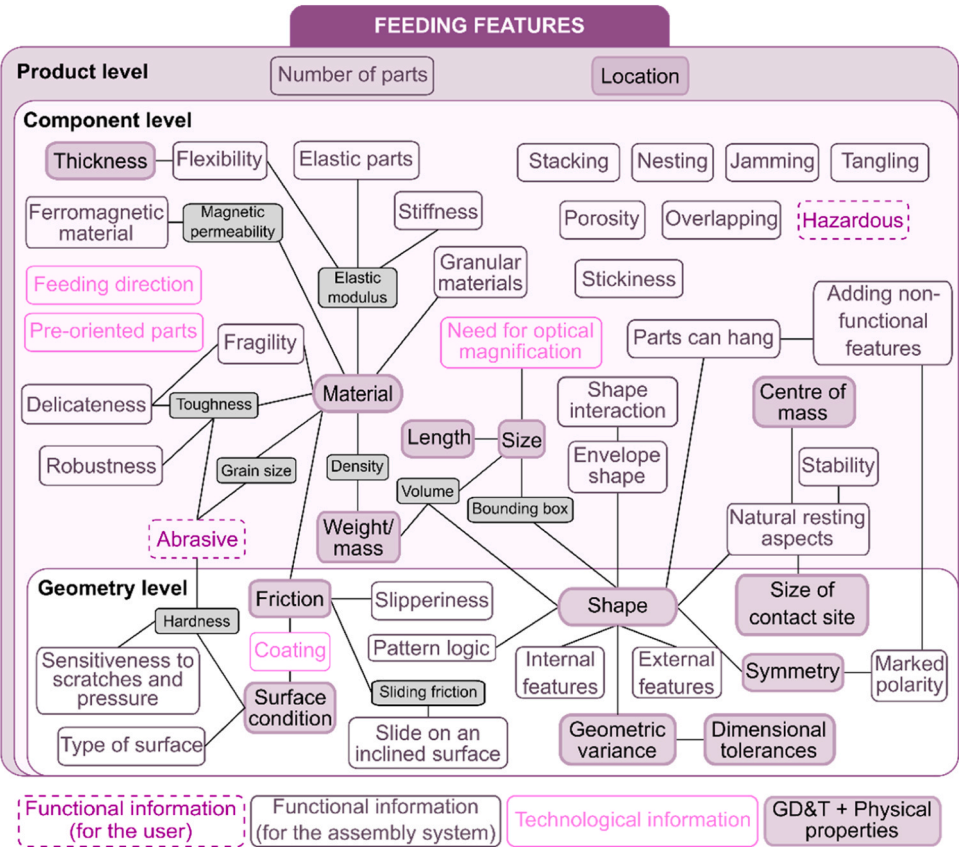


Fig. 6. Feeding-related concepts at different level of hierarchy.

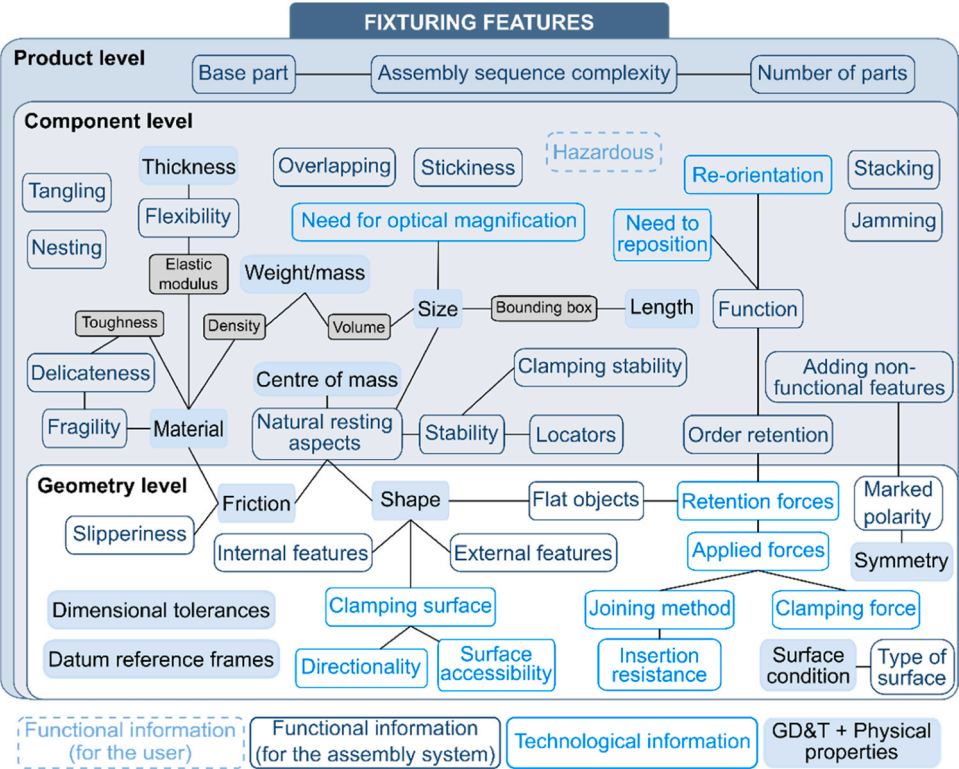


Fig. 7. Fixturing-related concepts at different level of hierarchy.

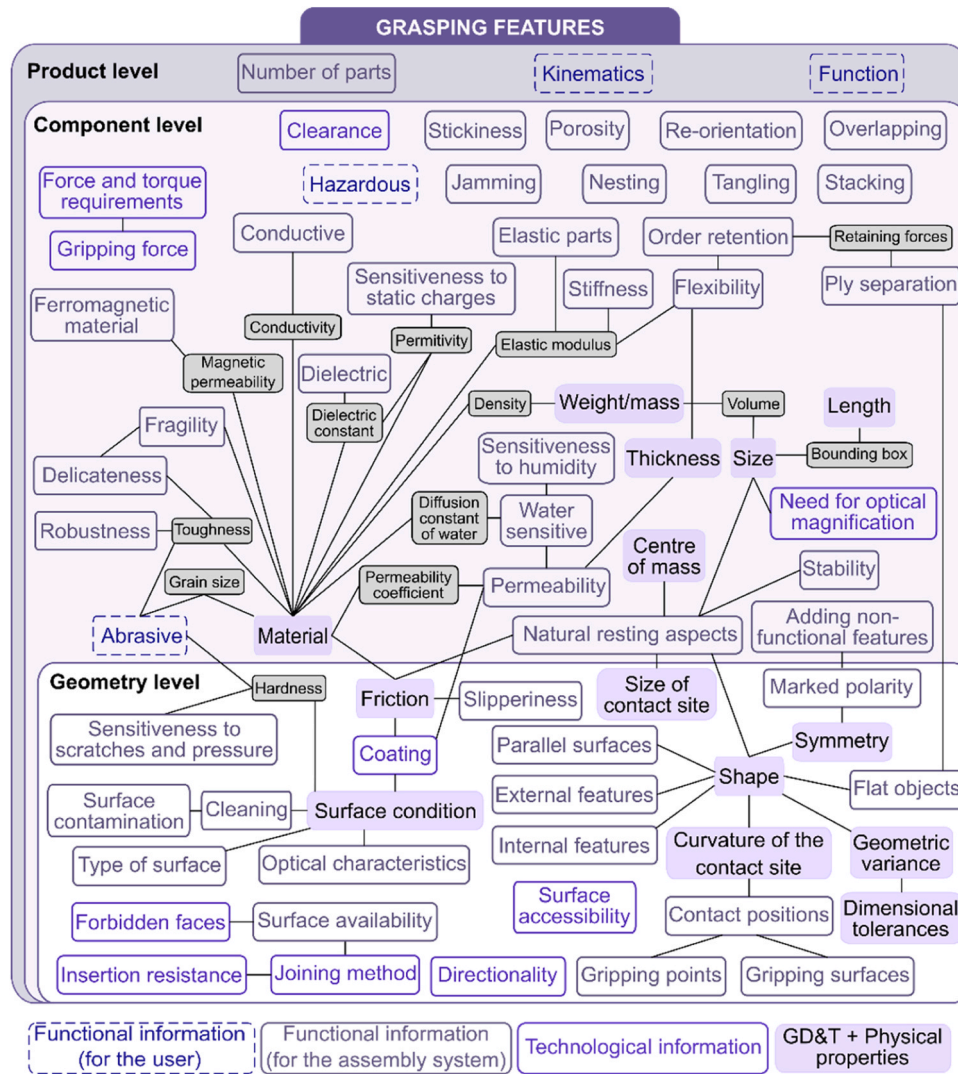


Fig. 8. Grasping-related concepts at different level of hierarchy.

(CAX-IF) [81–84], a suitable mechanism for representing the concepts within the product model was identified: user-defined attributes. The mechanism allowed the timely addition of product properties linked to the product structure, as shown in Fig. 9. The timeliness arises from its flexibility to accommodate the properties in the product model as the design evolves.

By employing the proposed model, handling-related properties could be integrated at different levels without a completed shape representation or assembly structure. For instance, if the design is still in the conceptual stage, the product property can be linked to the overall product; later, when reaching a detailed design, the property can be refined and attached to the specific component or geometric shape entity being affected.

Once the representation mechanism was clear, the results of the relational analysis could be integrated into the modelling strategy. Since the found concepts already considered the product structure and the type of information they carry, only a representation complying with the standard and concept nature was needed to be identified, i.e., text or numerical value representation.

It is important to note that STEP provides several representation constructs, from text to numerical values and measurements, including value qualifiers, units, and environment data for characterizing the measurement conditions. However, considering the points at the end of Section 4.1, in this work, the representations were suggested based on

how the stakeholder would use the handling-related information. Thus, often, synthesized information would need to be represented. A simplified version of the type of representations proposed for relevant concepts is presented in Table 7. A complete table is available in Appendix C.

It is apparent from this table that some concepts were already considered in several application modules of the STEP standard. For instance, ISO 10303–1039 already considered volume a geometric validation property and a CAX-IF recommended practice suggested its representation method. Similarly, ISO 10303–1681 described the representation of the material identification and material properties. However, for straightforward use in assembly planning, the overall size and estimated weight are more practical than the volume of the product, and an assessment of the product as being flexible or not (according to prior internally defined policies) is more beneficial than its accurate modulus of elasticity. For different stakeholders, different product information granularity is required, not always a detailed description of their characteristics provides the best input.

4.3. Case study results

A case study according to the protocol outlined in Section 3.3 was developed to illustrate the proposed model.

Following the established protocol, information about the pneumatic

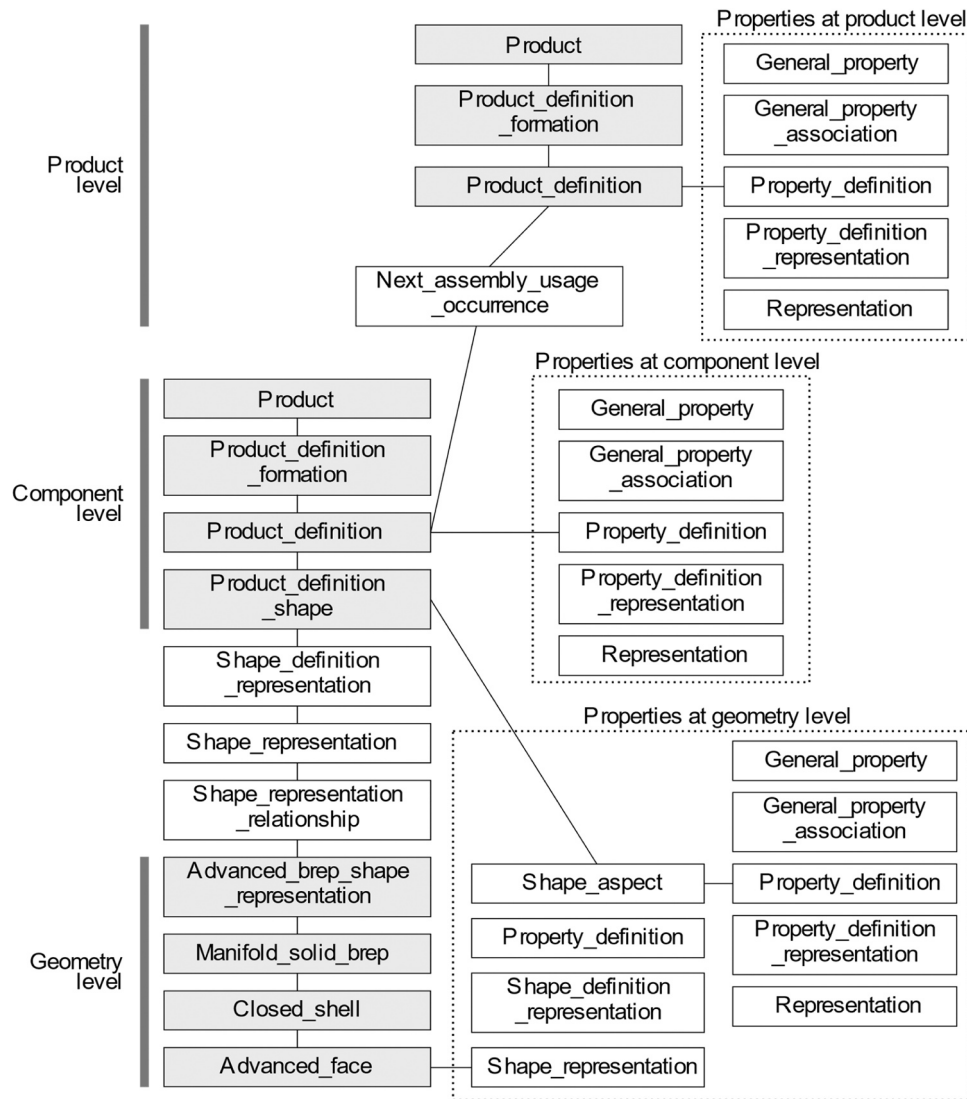


Fig. 9. User-defined properties at different hierarchical levels within the product model according to [82].

Table 7
Sample of relevant concepts with their suggested representation.

Concept	Suggested representation	Type of value	STEP-part
Size	Bounding_box	Cartesian point (2)	10303 – 42:2022 (Also, in scope for STEP Ed. 4)
Shape	Descriptive_representation_item	Text	10303 – 1030:2019 10303 – 45:2019
Weight/mass	Mass measure with unit (qualified)	Real + SI_unit	10303 – 1030:2019 10303 – 41:2022
Tangling	Descriptive_representation_item	Text	10303 – 1030:2019 10303 – 45:2019
Symmetry	Value_representation_item + Centre_of_symmetry	Text + Axis/Point/Plane	10303 – 43:2022 10303 – 1130:2018
Flexibility	Material_property_representation: Descriptive_representation_item	Text	10303 – 1681:2018 – 11
Centre of mass	Centre of mass	Cartesian point	10303 – 1350:2018 10303 – 42:2022
Material	Material designation	Text	10303 – 1681:2018 – 11
Clamping surface	Shape_aspect + Item_identified_representation_usage	Advanced face/ Other shape element	10303 – 1032:2023
Friction coefficient	Measure_representation_item (qualified) + Shape_aspect_relationship + Shape_aspect (2) + Item_identified_representation_usage	Real	10303 – 1030:2019 10303 – 45:2019

cylinder subject of this analysis was extracted from internal and external sources. To select the features represented in the case study, technical specifications and assembly details of the product were examined. Three criteria were considered for this selection: frequency of use across a wide range of products, diverse nature (to test the capability of the model to represent different types of information), and usefulness for handling tasks, according to the focus of this work. Ultimately, the features selected for this case study were the ‘number of parts’ and the features depicted in Fig. 10.

Later, the available product model in STEP was enriched with information according to the proposed model and the suggested representations. The information was added with the use of the software AGREE™ [96] according to the STEP AP242 Ed 3 schema.

For illustrative purposes, the model was segmented to emphasize the represented concepts. Fig. 11 shows the product structure according to the STEP standard, specifically the product level (the top entities) and component level (entities following the *Next_assembly_usage_occurrence* entity). The concept ‘number of parts’, common for the three handling features categories, was modelled at the product level, and represented by an integer value.

Following the product structure, Fig. 12 presents the component level and the beginning of the geometry level of the component Piston. At the component level, the feeding-related concept of ‘feeding direction’ is represented by a *Direction* entity. At the component level but tied to the shape, the ‘centre of mass’, ‘symmetry’, and ‘bounding box’ properties are represented. The common concept ‘symmetry’ was represented by a *Value_representation_item* stating the type of symmetry and the *Centre_of_symmetry* entity relating a geometrical element (in this case an *Axis2_placement_3d*) to be used as the symmetry reference (other geometrical entities can be used as reference, such as a plane, a point, a curve or a surface). In the same manner, the ‘centre of mass’ was represented by a *Cartesian_point* containing its coordinates, and the ‘bounding box’ size was represented using two *Cartesian_point* entities.

Focusing on the FrontCap component, at the geometry level tied to four *Advanced_face* entities, the grasping-related concept ‘forbidden face’ is represented with text (Fig. 13). It is important to note that a *Shape_aspect* and several *Item_identified_representation_usage* entities were

required in this case to select multiple faces in the component. A similar strategy is used to represent the fixturing-related concept of ‘clamping surface’.

Lastly, ‘friction_coefficient’, a common concept was represented as a positive measure representation. This representation was characterized with a qualifier indicating that the value is the minimum acceptable (Fig. 14). Since friction is a concept defined by the interaction of two surfaces, the representation needed to identify the surface in each component and the property was tied to the association of those surfaces, the entity *Shape_aspect_relationship*.

Due to space restrictions, the rest of the concepts and their representations are available in the complete model shown in Appendix D.

Finally, according to the protocol, the resulting enriched model was validated by using two external tools complying with the STEP standard: the JSDAI library [97] that validated the file against the STEP AP schema, and the STEP File Analyzer [98] checking the compliance with CAX-IF praxis, both finding no syntactic errors, no erroneous instances, and no violated rules in the file.

Together, these results provide important insights into the subject of assembly features, especially handling features for automatic assembly and the possibility of their representation within the product information model. The extracted and categorized handling features offered a perspective on the required information and the disparity between its representation and utilization by the stakeholders. Also, both the proposed model and the outcomes of the case study revealed potential avenues for leveraging information representation to facilitate collaborative cross-disciplinary communication in product design and assembly planning. The next chapter, therefore, moves on to discuss the challenges towards this goal.

5. Discussion

This work aimed to fill the existing gap in the representation of handling information for automatic assembly from early product design. With this aim, a proposed mixed methodology allowed the identification of product characteristics valuable to handling tasks, building a product model that exposed the relationships between them, and proving the

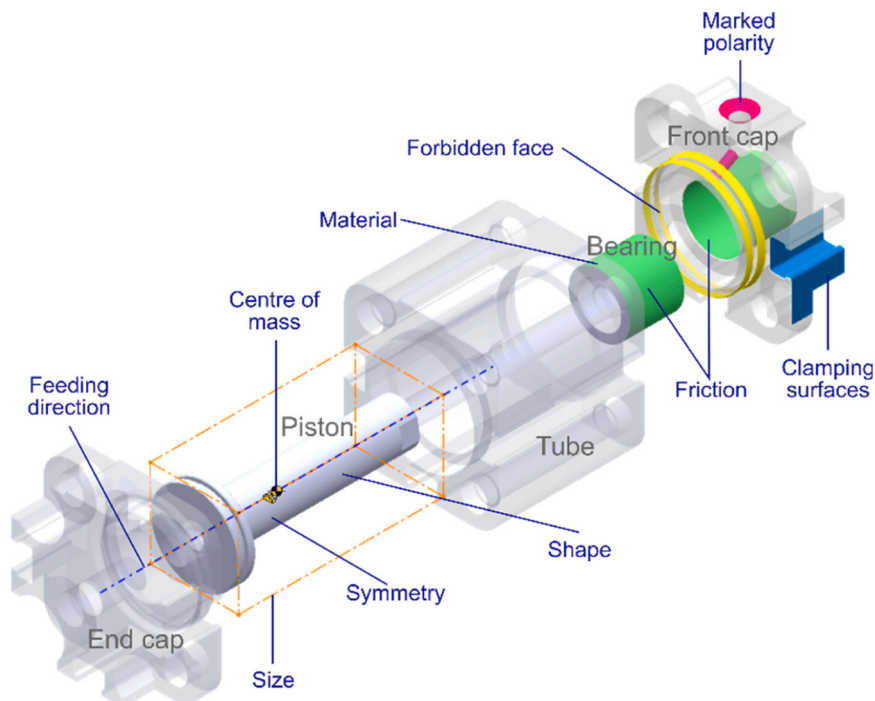


Fig. 10. Selected handling features to add to the product model.

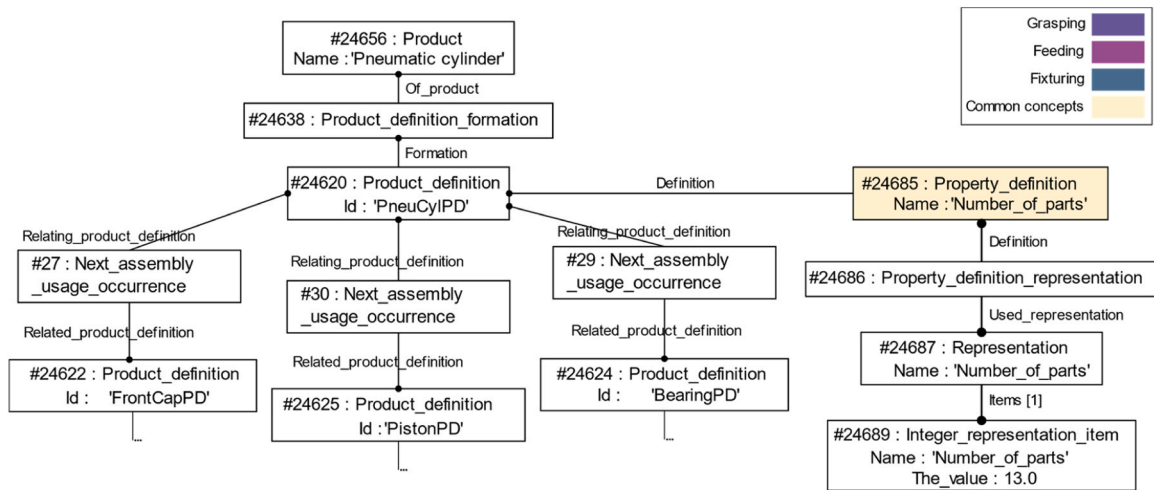


Fig. 11. Properties at product level.

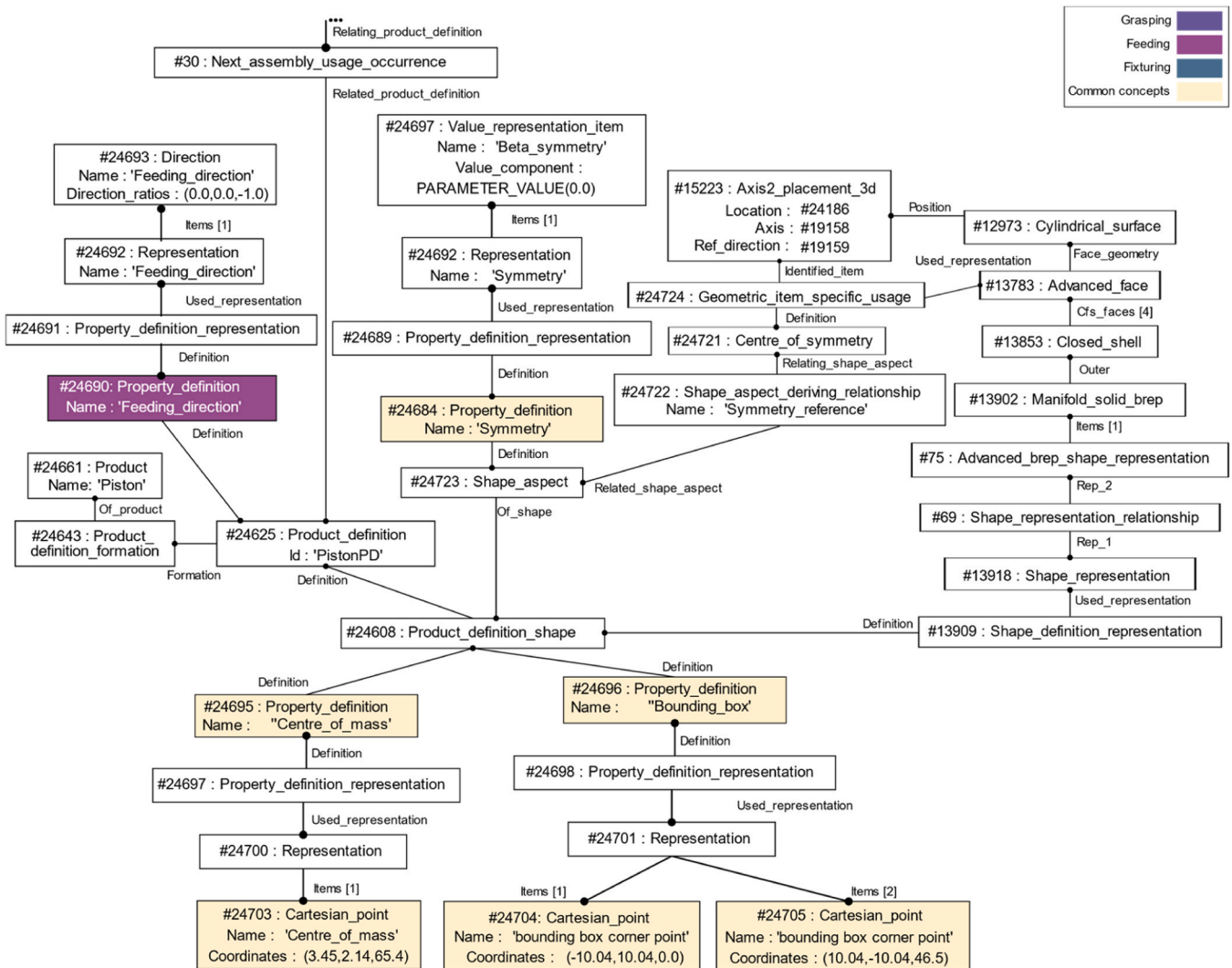


Fig. 12. Properties at component and geometry level.

validity of such a model in a case study. The findings from this study offer possibilities for further discussion.

First, despite extensive research on assembly-related tasks, certain

definitions have remained ambiguous, particularly concerning the distinctions between material handling in the logistics domain and handling within the context of assembly. Considering the growing

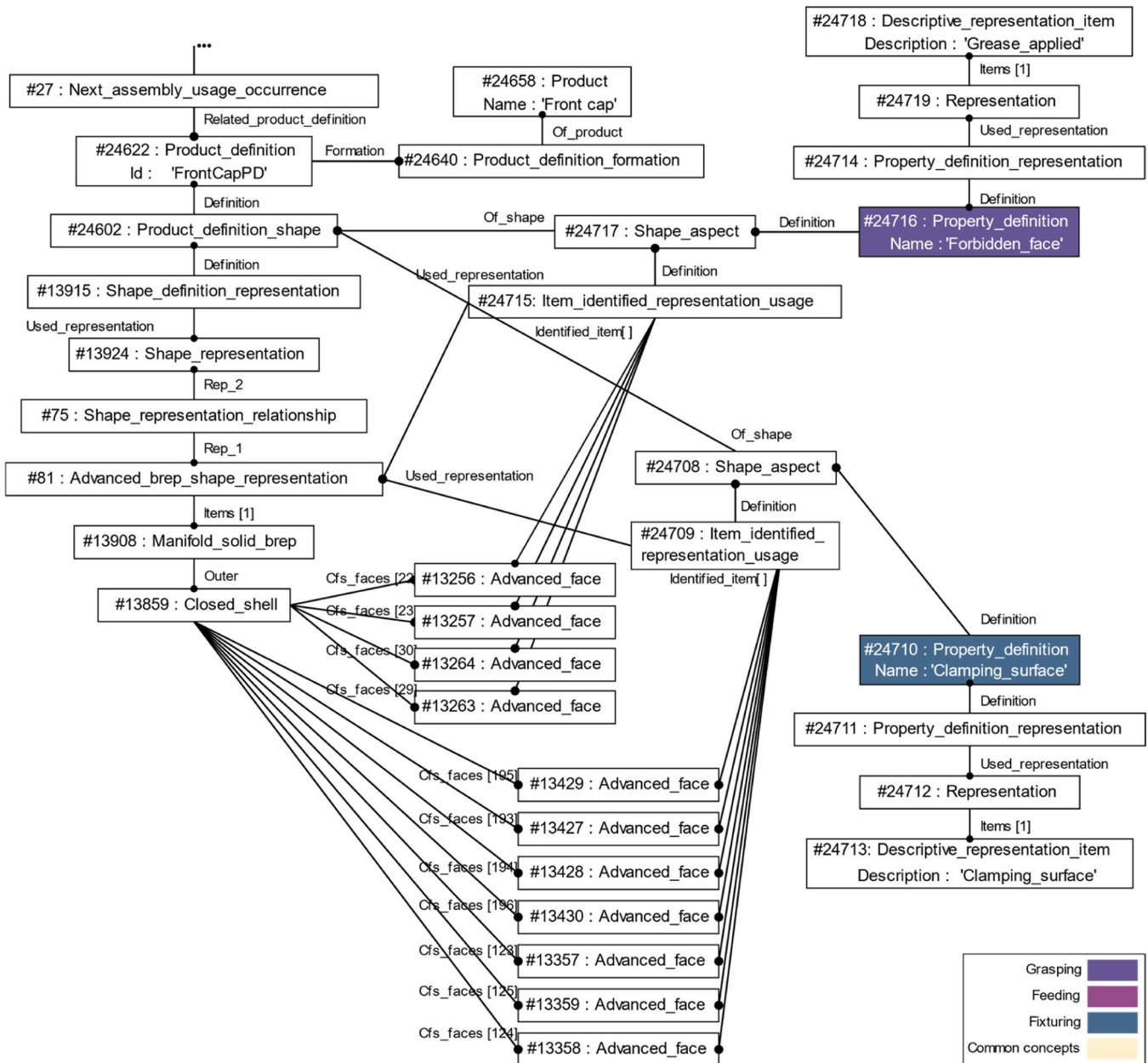


Fig. 13. Properties at geometry level (1).

implementation of automatic production systems, these definitions become relevant for a well-defined manufacturing sequence.

Second, feeding, fixturing, and grasping tasks demand more detail when their execution is automatic than when executed manually. For instance, manual assembly tolerates a component delivered to the assembly site in any orientation since a human operator can adjust it dynamically. Instead, automatic assembly demands a precise orientation for a smooth continuation of the pre-programmed assembly tasks without halting. However, as found in the literature, the level of detail also depends on the targeted subprocess. The proposed approach is flexible enough to capture information with different levels of detail since the product characteristic is mapped to the model through a property and its respective information to a representation. Then, one property can be defined by several representations, and a representation can adopt any data type depending on its accuracy. For instance, at early design stages, a property could be described just as text, but later, specific parameters can be established to represent it, either as single values or ranges. Complex representations such as cartesian points or geometric

elements (e.g., planes or axes) and even spatial transformations can be attached to the properties due to the modelling standard used. Then, the level of detail is determined only by the chosen representation.

Third, the studied literature and the large number of extracted common and overlapping concepts confirmed the strong relationship between product characteristics and handling processes. This relationship also spotlighted the interconnectivity across handling processes, i. e., certain handling features can change their role depending on the assembly stage. For instance, a set of surfaces in the product shape forming a groove or slot used for feeding, once delivered to the assembly site, could also be used for fixturing or grasping. This change of role is known as feature conversion in the literature. However, we represent the product characteristics relevant to the handling processes without labelling them as part of one specific type. With this in mind, they can have different functions for different handling processes.

Even when though work made an effort to compile a comprehensive list of product characteristics for handling, further work is needed to ascertain the information that will be most valuable to each stakeholder

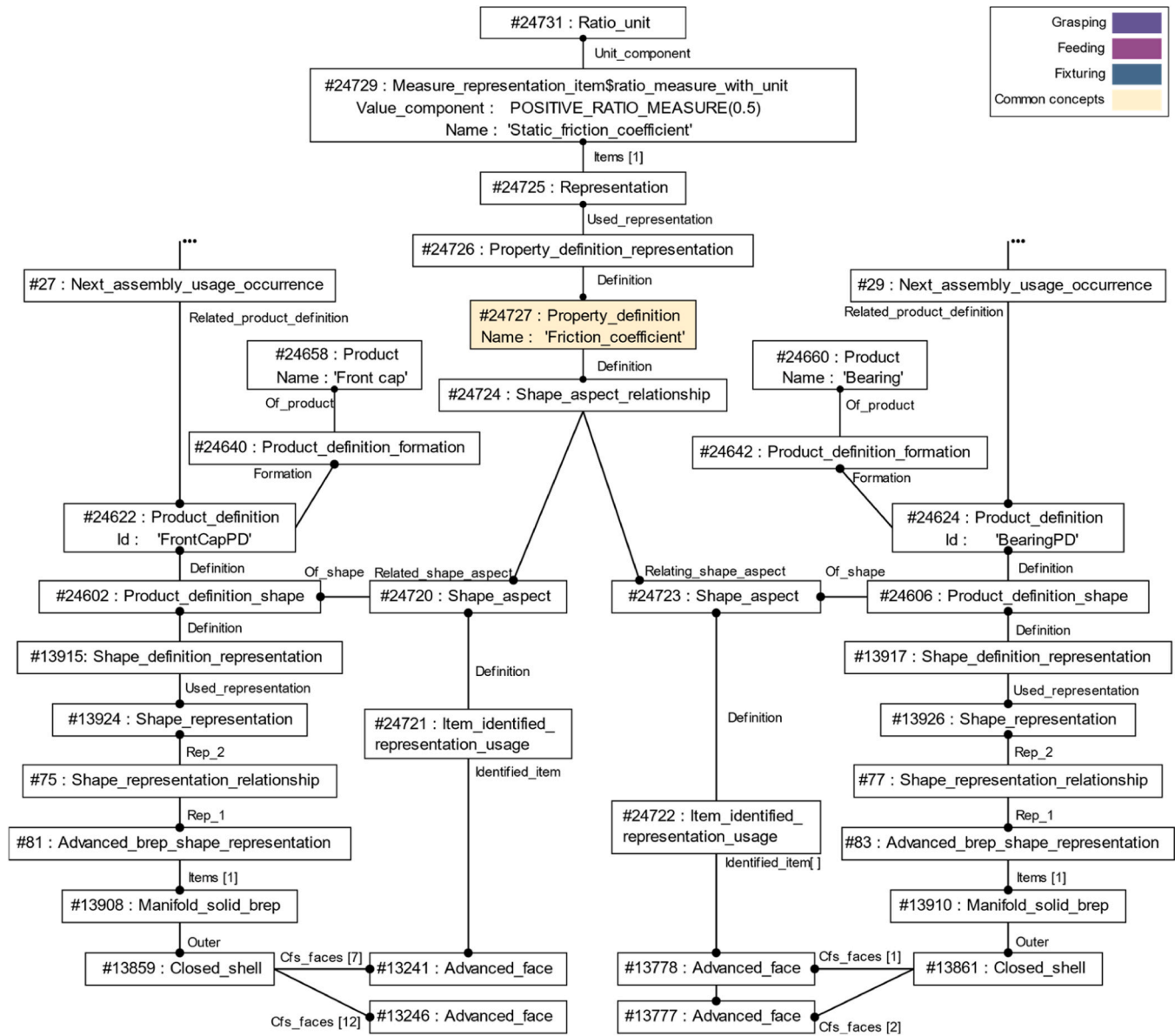


Fig. 14. Properties at geometry level between two components.

according to its priorities. A similar effort is required to determine the most appropriate representation of that information within the proposed model.

Besides, the required product characteristics and their relationships will change depending on the nature of the product. Thus, a specific analysis of the concepts and their definitions is required for each product family to adapt the model to different industries by incorporating appropriate concepts influencing handling-related processes.

Fourth, regarding the information required for feeding, fixturing, or grasping besides technological information and GD&T, this work proposed to make a distinction between two types of functional information: from the user and the production system perspective. Functional information from the user perspective usually influences the product design at the product or component level, e.g., by demanding components for expanded capabilities or limiting relative movement between components. Conversely, functional information from the production system perspective predominantly affects the product at the geometry level, e.g., by introducing shape features to aid production tasks or setting up material requirements compatible with existing equipment. Concerning technological information, even when this information is

scarce at early design stages, providing a hint of the possible assembly processes helps to constrain the material selection or define clearance between components, for example. Then, this information could influence the product design at the component or geometry level. Finally, GD&T and physical properties information may not be fully available at the beginning of the product design, but defining their nominal, maximum/minimum, or estimated values could facilitate an early production planning kick-off.

Fifth, changing the focus to the proposed model, it must be recalled that this is one of many viable modelling solutions in the CAD context and is therefore constrained by the adopted standard. The model presented in this work employed the method to represent user-defined attributes within STEP AP242 to integrate the identified handling-related concepts in the product structure. Although the ISO 10303 standard family STEP provides multiple capabilities for modelling mechanical and electromechanical products, which enables the evolution of the model according to the product nature, a unified definition of the presented handling concepts is essential. Such specification could be provided within the STEP standard, an implementor's specification, or a separate dictionary.

Sixth, it is important to note that the proposed representation of handling-related concepts aims to enrich the (geometrical) product model with information valuable for assembly planning, by synthesizing this information for immediate use and location. On the other hand, the STEP standard also defines geometric and assembly validation properties that help validate the data exchange by comparing product characteristics between the sender and receiver system to ensure appropriate exchange and information integrity. In this sense, although some properties proposed in this work may have similarities with other geometric validation properties, their different purposes should be unmistakable.

Seventh, implementing the proposed model is expected to influence product design and the design of dedicated specialized equipment (tools) for handling processes, particularly in the way of working.

Regarding product design, the model encourages early integration of production-related aspects, necessitating extensive communication and agreement between design and production personnel, fostering collaboration. This collaboration, combined with the model's capability of storing this information, prevents disregarding production considerations later. Because of this, the number of design iterations due to the product being incompatible with automatic assembly can be reduced. As the product design evolves to a more detailed one, more precise production aspects can be defined in collaboration. However, this practice may require a significant time investment for designers to add this information to the model, though it can be compensated with fewer design iterations later. In addition, the active involvement of production and design personnel would be required to exchange knowledge and clarify needs, leading to establishing the best possible design alternative.

Concerning the design of specialized tools, even when details are vague in the early design stages, equipment manufacturers can take advantage of the information in the model to discard unsuitable alternatives, e.g., reducing gripper alternatives based on incompatibility between working principle and product material. In this way, the product and tool design can evolve in parallel. By the time the product reaches the detailed design stages, the manufacturer is expected to have enough information to start the conceptual design of the tool and be ready to take over the project once the product design finishes. This parallel evolution can significantly reduce the development time for the equipment, ultimately shortening production preparation time.

Eighth, considering the potential influence in the product design and design of dedicated specialized equipment mentioned above, the proposed model could, in the long term, facilitate automatic process planning for assembly processes. By carrying and communicating detailed production-related information, this model can be integrated into future software applications specialized in automatic process planning, which could exploit the embedded information, extract it, and generate process plans accordingly. This integration would reduce misalignments in the design-to-production workflow.

In general, the proposed solution establishes a bridge between the product and resource lifecycle and offers a space for the designer and planner to share ideas and assess the impact of design choices from the early stages: design adds shape features, production translates their implication for the assembly system, and external suppliers extract requirements for equipment design, as shown in Fig. 15.

6. Conclusion

This study sought to investigate the handling features within the automatic assembly domain. It aimed to determine how to include them within the product model from early product design stages and how this approach could foster collaboration between design and production.

Aligned with the intelligent product perspective, this research delved into the relationship between product design and production preparation, focused on the handling processes, obtaining three main contributions.

First, this research has synthesised evidence confirming the long-

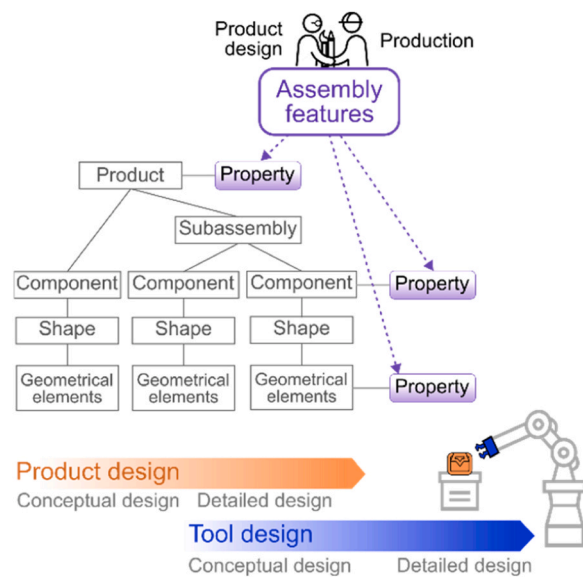


Fig. 15. Scenario with the implementation of the proposed solution.

claimed relationship between product characteristics and handling processes. Further, it has refined the need for specific details in the product design to facilitate automatic feeding, fixturing, and grasping processes. It also consolidated insights regarding the links among product characteristics, which can clarify the effects their variations have on the studied processes. Thus, the extracted concepts and mapped relationships product of the relational analysis constitute the theoretical contribution of this work. Further work is required to determine existing relationships between missing concepts and the handling subprocesses since this study was limited to the information in published literature.

Second, a modelling approach to integrate the handling features into the product information model compliant with the ISO 10303 standard was proposed. The proposed approach takes advantage of the flexibility of the standard and its multiple modelling constructs to represent information of a diverse nature in a structured way, hence valid to all (electro)mechanical products represented in this standard.

Another practical and third contribution is the improved collaboration between design and production achieved through the integration of product-related aspects early in the design process. This collaboration could lead to establishing parallel product and tool design workflows, which enables an upfront tool design, benefiting the equipment manufacturer.

A natural progression of this work is to assess the impact of the implementation of the proposed approach in an industrial environment, and to analyse a strategy to link the identified handling features in the product model to the assembly system model to close the product-process-resource path. Other areas of interest are the study of the conversion among different types of handling features, and from handling to insertion features, automatic recognition of handling features, and building a model-based definition for assembly processes.

CRedit authorship contribution statement

Antonio Maffei: Writing – review & editing, Writing – original draft, Supervision, Conceptualization. **Nathaly Rea Minango:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Mikael Hedlind:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Conceptualization.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests. Financial support from the H2020-MSCA-ITN DiManD project funded by the European Union's Horizon 2020 under grant agreement No. 814078.

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Appendix A. Assembly feature types

Assembly feature type	Source
Connect / join/insert	[2,28,46–48,66,68,95,99–110]
Handling	[2,28,47,48,66,68,95,101,104–106,108,109]
Position	[28,102,103,105,106,110–112]
Feeding / Separation /Buffering	[28,47,66,68,101,106,107,110]
Fixturing / retain / securing	[47,68,101,106,107,113]
Mating constraints	[49,68,109,114–116]
Kinematic-related	[106,107,112,114,117]
Grasping / gripping	[47,68,101,110,115]
Attachment	[46,114,118]
Support process / complementary / work	[107,108,118]
Inspection / checking /measure	[48,106,107]
Special operations	[48,106,108]
Shape-related	[118–120]
Screwing	[102,103]
Logistics / Transport	[66,104]
Human-machine interaction	[48]
Structure	[113]
Information exchange	[48]
Skeleton	[120]
Operation	[113]
Changing quantity	[106]
Preparation	[104]
Finalization	[104]
Quality	[104]
Commissioning	[108]
Part-of	[117]
Structuring	[117]
Parametric	[117]
Constraints	[117]
Behaviour	[117]
Function	[117]

Appendix B. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.jmsy.2024.11.012](https://doi.org/10.1016/j.jmsy.2024.11.012).

Appendix C. Concept representations

Concept	Suggested entity	Type of value	STEP-part
Surface accessibility	Direction	Real	10303 –45:2019
Directionality	Direction	Real	10303 –45:2019
Feeding direction	Direction	Real	10303 –45:2019
(Re-orient) Need to reorient	Descriptive_representation_item	Text	10303 –1030:2019
/reorienting capabilities			10303 –45:2019
Pre-oriented parts	Descriptive_representation_item	Text	10303 –1030:2019
			10303 –45:2019
Need to reposition	Cartesian point	Real+ Text	10303 –42:2022
	+ Descriptive_representation_item		10303 –45:2019
Location	Cartesian point	Real+ Text	10303 –42:2022
	+ Descriptive_representation_item		10303 –45:2019
Datum reference frames	Cartesian point	Real+ Text	10303 –42:2022
	+ Descriptive_representation_item		10303 –45:2019
Stability	Direction	Real	10303 –45:2019
Centre of mass	Centre_of_mass	Cartesian point	10303 –1350:2018
			10303 –42:2022
Natural resting aspects	Descriptive_representation_item	Text	10303 –1030:2019
			10303 –45:2019
Clamping stability	Direction	Real	10303 –45:2019

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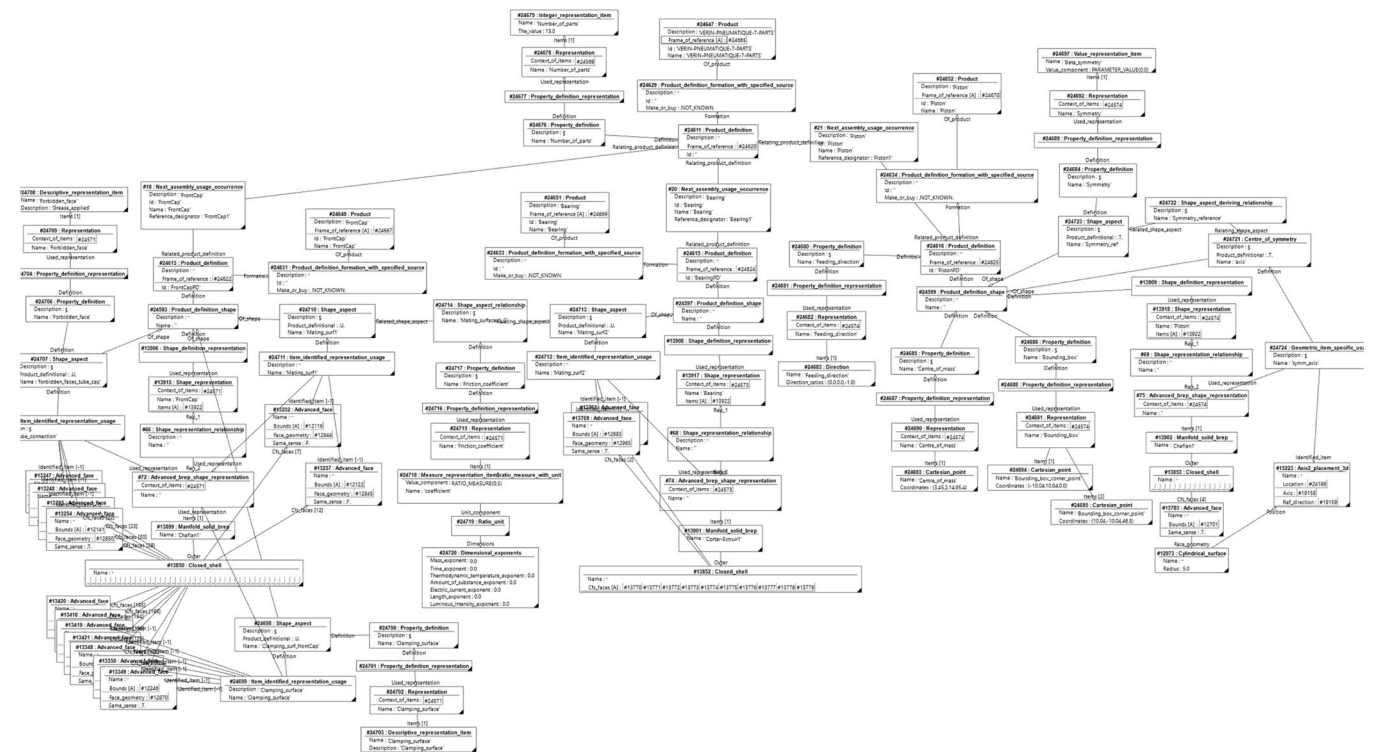
Concept	Suggested entity	Type of value	STEP-part
Surface condition	Surface_condition		10303 –1110:2019
Type of surface	Descriptive_representation_item	Text	10303 –1030:2019 10303 –45:2019
Surface contamination	Descriptive_representation_item	Text	10303 –1030:2019 10303 –45:2019
Coating	coating_layer		10303 –1110:2019
Optical characteristics	visual_appearance		10303 –1110:2019
Necessity for optical magnification	Descriptive_representation_item	Text	10303 –1030:2019 10303 –45:2019
Clearance	assembly_constraint (AM)	Binary_assembly_constraint	10303 –1794:2014
Cleaning	treatment_result		10303 –1110:2019
Ply separation	Descriptive_representation_item	Text	10303 –1030:2019 10303 –45:2019
Order retention	Descriptive_representation_item	Text	10303 –1030:2019 10303 –45:2019
Insertion resistance	Descriptive_representation_item	Text	10303 –1030:2019 10303 –45:2019
Joining method	Descriptive_representation_item	Text	10303 –1030:2019 10303 –45:2019
Number of parts	Integer_representation_item	Integer	10303 –45:2019
Base part	assembly_root (function)	Boolean	10303 –109_2004
Assembly sequence complexity	Descriptive_representation_item	Text	10303 –1030:2019 10303 –45:2019
Surface availability (after previous step)	Descriptive_representation_item	Text	10303 –1030:2019 10303 –45:2019
Forbidden faces (or threaded faces)	Descriptive_representation_item	Text	10303 –1030:2019 10303 –45:2019
Kinematics (movement, speed)	kinematic_property_definition_representation	Real	10303 –105:2019
Symmetry	Value_representation_item + Centre_of_symmetry	Text + Axis/Point/Plane	10303 –43:2022
Marked polarity	Descriptive_representation_item	Text	10303 –1030:2019 10303 –45:2019
Shape	Descriptive_representation_item	Text	10303 –1030:2019 10303 –45:2019
Shape interaction (between part and bowl/track)	Descriptive_representation_item	Text	10303 –1030:2019 10303 –45:2019
Envelope shape	Descriptive_representation_item	Text	10303 –1030:2019 10303 –45:2019
Geometric variance	Shape_variation_tolerances (IR) Measure_with_unit + qualifier	Real+unit+qualifier	10303 –47:2022
Pattern logic	Descriptive_representation_item	Text	10303 –1030:2019 10303 –45:2019
Parallel surfaces	shape_aspect + Descriptive_representation_item	Text	10303 –1030:2019 10303 –45:2019
Adding non-functional features	Descriptive_representation_item	Text	10303 –1030:2019 10303 –45:2019
Internal features	shape_aspect + Descriptive_representation_item	Text	10303 –1030:2019 10303 –45:2019
External features	shape_aspect + Descriptive_representation_item	Text	10303 –1030:2019 10303 –45:2019
Parts can hang	shape_aspect + Descriptive_representation_item	Text	10303 –1030:2019 10303 –45:2019
Flat objects	Descriptive_representation_item	Text	10303 –1030:2019 10303 –45:2019
Length	Bounding_box	Cartesian point (2)	10303 –42:2022
Size	Bounding_box	Cartesian point (2)	10303 –42:2022
Thickness	Measure_with_unit	Real	10303 –45:2022
Weight/mass	Mass measure with unit (qualified)	Real + unit	10303 –1030:2019 10303 –41:2022
Stacking	Descriptive_representation_item	Text	10303 –1030:2019 10303 –45:2019
Jamming	Descriptive_representation_item	Text	10303 –1030:2019 10303 –45:2019
Overlapping	Descriptive_representation_item	Text	10303 –1030:2019 10303 –45:2019
Stickiness	Descriptive_representation_item	Text	10303 –41:2022 10303 –45:2019
Slipperiness	Descriptive_representation_item	Text	10303 –41:2022 10303 –45:2019
Applied forces	Force_data_element	Real + Unit	10303 –1753:2018
Force and torque requirements	Force_data_element	Real + Unit	10303 –1753:2018
Clamping force	Force_data_element	Real + Unit	10303 –1753:2018
Gripping force	Force_data_element	Real + Unit	10303 –1753:2018
Retention forces	Force_data_element	Real + Unit	10303 –1753:2018
Clamping surface	Force_data_element	Real + Unit	10303 –1753:2018

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Concept	Suggested entity	Type of value	STEP-part
Locators (Locating faces/ locating points)	Cartesian point	Real+ Text	10303 –42:2022
Size of contact site	+ Descriptive_representation_item	Real + unit	10303 –45:2019
Curvature of the contact site	shape aspect + value_with_unit	Real + unit	10303 –45:2019
	Descriptive_representation_item	Text	10303 –1030:2019
			10303 –45:2019
Gripping points	Cartesian point	Real+ Text	10303 –42:2022
	+ Descriptive_representation_item		10303 –45:2019
Gripping surfaces	shape aspect	Text	10303 –45:2019
	+ Descriptive_representation_item		
Contact positions	Cartesian point	Real+ Text	10303 –42:2022
	+ Descriptive_representation_item		10303 –45:2019
Sensitiveness to scratches and pressure	Hardness	Measure_item + Text	10303 –1110:2019
Slide on an inclined surface	Descriptive_representation_item	Text	10303 –1030:2019
			10303 –45:2019
Friction	Material_property	Material_identification	10303 –1681:2018
Sensitiveness to static charges	Material_property	+ Material_property_value_representation + Qualifier	10303 –1110:2019
Sensitiveness to humidity	Material_property		10303 –1110:2019
Water sensitive	Material_property		10303 –1110:2019
Fragility	Material_property		10303 –1681:2018
Delicateness	Material_property		10303 –1681:2018
Robustness	Material_property		10303 –1681:2018
Flexibility	Material_property		10303 –1681:2018
Elastic parts	Material_property		10303 –1681:2018
Stiffness	Material_property		10303 –1681:2018
Permeability	Material_property		10303 –1681:2018
Porosity	Material_property		10303 –1681:2018
Hazardous	Material_property		10303 –1681:2018
Abrasive	Material_property		10303 –1681:2018
Granular materials	Descriptive_representation_item	Text	10303 –1030:2019
			10303 –45:2019
Function	Descriptive_representation_item / Functional_element	Text	10303 –1216:2008

Appendix D. Complete case study model



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