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Novel Computer-Aided Design-Based Collaboration Framework for the Conceptual–Embodiment Design Phase

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Abstract: Collaborative production is growing in its importance to the global economy, and along with it, so are other collaborative activities along the production chain, such as collaborative design. Nowadays, collaborative detail design can be implemented using Computer-Aided Design (CAD) through task sharing and Product Lifecyle Management (PLM) systems, but collaborative conceptual design is still poorly supported by CAD. Therefore, there is a need for a dedicated CAD platform that can support collaborative conceptual design as well. This paper contains the basic architecture for a CAD system used in collaborative conceptual–embodiment design, the proposed workflow for using the CAD system, and the design comparison method included in the system, that together comprise a CAD-based collaboration framework for conceptual–embodiment design. The framework is based on Coevolution Design Theory and developed such that it can be used to design complex products in an efficient, collaborative manner. A simple case study describing the use of the framework is included to illustrate how the framework can be used to design a product. In the future, this framework can be used to further develop and build a fully functional CAD system that will help designers to engage in a global collaborative setting.

Keywords: collaborative design; conceptual design; embodiment design; computer-aided design

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1. Introduction

Collaborative production can be defined as a cooperative activity performed by more than one entity in a collective network to design, produce, and distribute products that have been agreed upon by the entities in the collaborative network [1]. Collaborative production is expected to contribute EUR 26 billion to the global economy each year [1]. The importance of collaborative production in the global market has increased since the advent of the global supply chain and it has increased even more through the emergence of Industry 4.0, which focuses on, among other things, real-time connectivity and communication between different entities.

As a part of the collaborative production activity, collaborative design has its own challenges that complicate the process. Design activity is inherently a complex and unstructured process; as such, it is difficult to develop a technology that can improve the efficiency of the design process [2]. Computer-Aided Design (CAD) is a term which can collectively be used to refer to the software technology used by designers to aid in designing, usually for complex electromechanical products.

Goel et al. stated that the CAD of the future should embody the concept of the four Cs, which are collaborative, conceptual, creative, and cognitive [3]. This means that CAD should facilitate collaborative design activities, should be deployed more in the conceptual design phase, should aid in the creative process of designing, and should be made in accordance with the human cognitive state of the design process. A glance at the state of CAD implementations popular in the industry right now has shown that these concepts are not yet embodied in CAD systems.

CAD applications are usually used by individual designers and where collaborative action is needed, it is facilitated by Product Lifecyle Management (PLM) modules, which are, essentially, a comprehensive CAD database for multiple designers to collaborate on creating a product by enabling file sharing, file tracking, and the editing of multiple CAD files that can be combined to create a product. These tools are essential for coordinative activities, which are a subset of the collaborative activities that are characterized by task delegation for the involved parties, such as when each designer is tasked with designing a specific part of the whole product [4]. On the other hand, tools to support cooperative activities, such as when multiple designers are tasked in co-designing a single part, are still not in widespread use in the industry.

Furthermore, popular parametric CAD applications are tailored for use in the detail design phase instead of the conceptual design phase, where the focus is on providing detailed dimensions and geometric relationships between model entities [5]. Due to this, these systems do not yet provide much creative assistance to designers. To the best of our knowledge, popular CAD applications have also not been developed considering human cognitive processes. All of these findings helped to guide the formulation of the research question, which is, "How can CAD be used to facilitate the exchange of design ideas between designers at the early design phase such that it will lead to efficient collaborative design?".

This paper details part of an effort to create a collaborative CAD system that is aimed for use in the early phases of design, namely, the conceptual–embodiment design stage. To that end, we first chose Cognitive Design Theory to serve as the basis of our CAD platform. We then translated the theoretical framework into CAD modules that correspond to the theory. As the specific use case of the proposed system is quite different from the popular use of CAD, we further formulated the workflow and architecture of the system. In particular, as the collaborative conceptual–embodiment design process will create multiple conceptual designs for a given product, this research will also introduce a method for choosing the best design at the conceptual–embodiment design stage as a part of the developed CAD system. The proposed collaborative CAD system architecture, corresponding workflow for the use of the proposed system, and the embodiment design selection method included in the system are presented as a preliminary concept and validated through a simple case study to illustrate how the system is intended to work after its final development.

As such, the contributions of this paper are on the development of a novel architecture and workflow of the aforementioned CAD system. Specifically, the CAD framework is developed for use in a collaborative setting that will facilitate the creative exchange of ideas between designers, and is to be used in the early design phase, incorporating a Cognitive Design methodology to ensure its parts and function are in line with the natural design process. That is, the framework is developed exclusively to be in line with the four Cs concept of CAD mentioned earlier. Another novelty of the research is the development of a specific algorithm for rating and selecting the best conceptual–embodiment design alternative, which is based on the designer's confidence in whether a given design will be able to meet its intended function. The rest of this paper will give a review of the related previous research in the literature, followed by a detailed explanation of the developed CAD system, an example of how the model can be implemented for the design of a product, and lastly, a concluding section with further discussion and remarks about the proposed system and its future potential development.

2. Literature Review

As stated before, the topic of this research concerns collaborative CAD and conceptual design, including methods for deciding the best design out of various alternative conceptual designs. Therefore, the literature research that has been performed concerning these topics will be explained in this section.

One of the most popular approaches in the field of collaborative CAD is focusing on determining design constraints which are inviolable for the designers [6–8]. This approach can be used when several designers are each designing parts of a larger product. The design constraints are determined before the start of the design process, and they usually refer to certain parameters or dimensions that must be shared between interacting or assembled parts (interfaces). When a constraint is violated, all the affected designs are notified so that designers are forced to negotiate a compromise for the optimal design while considering the previously agreed-upon constraints. There are other methods in this approach, such as forcing the offending design to be changed so that it complies with the agreed-upon parameter before the design activity can proceed, or automatically modifying the changes in the agreed-upon parameter to all the designs that will be affected by that particular change (also known as the change propagation method). The concept of interfaces is much more important in coordinative activity where the design tasks are divided between designers; therefore, the interface is crucial to combine the disparate designs from multiple designers. On the other hand, in cooperative activity, where designers are concurrently acting on the same part of the design, the interface is more closely linked with the configuration of those parts into assemblies or subassemblies [4].

One of the approaches utilizing the change propagation method is to develop a method to fix the association management of CAD files comprising a global product in a Digital Mockup (DMU) environment [9]. This approach is suitable for highly technological products consisting of many assembly components. The collaboration process is needed when a small part of the DMU is taken and shared between partner entities to be modified according to the design needs. The modified files that are sent back will trigger the need for adjustments in the corresponding files to maintain the consistency of the DMU. As such, this research is focused on creating an efficient change propagation method that will minimize human intervention in the adjustment process.

Eltaief et al. continued the research by formulating change propagation strategies in a constraint-based collaborative design for parts and assembly, such that changes in a part will automatically trigger modifications to other parts in an assembly [10]. This is achieved by classifying the types of modifications that can be made in feature-based CAD, automatically capturing the relations between parts in an assembly, and specifying modification rules for each identified modification.

Dachowicz et al. has created a strategy model for sharing information in constraint-based collaborative design [11]. The need for the research arises from real-world collaborations between companies that involve the exchange of sensitive data files, even when the exchange is carried out between designer partners from other companies. The research formulated a number of equations to calculate the change in a designer's objective value and the corresponding secrecy value for the information, along with different information management strategies that correspond to the change in those values.

The constraint-based method is developed with the assumption that designers are engaged in a coordinative design activity. Coordinated design activities are useful for designing complex products with multiple components, where efficient design can be achieved by dividing the task of designing the parts of the final products between several designers simultaneously. Constraints in the interfaces of the assembled products will ensure that the final parts can be assembled into one coherent final product. This approach implicitly assumes that all designers in the process have knowledge on the form, shape, and function of the final product. This means that this approach is suitable for routine product design, which does not deviate much from an existing product solution.

On the other hand, much research in collaborative cooperative CAD focuses on the persistent naming problem, which is a special problem that arises in cooperative CAD when different designers are applying different transformative operations to the same CAD object. Lv et al. came up with a synchronization method based on a Conflict-Free Replicated Data Type (CRDT) for a cooperative CAD system [12], while in their subsequent research, the problem was solved through a novel method for selective undoing of operations in a cooperative CAD environment [13].

Other research on collaborative CAD focuses on how to efficiently distribute information about the design, including the CAD model itself, to other partner designers or other entities in the manufacturing chain. This goal was achieved through various methods and technology, such as through the use of a game engine, cloud server, VR device, and smart device [14–19]. The technologies used for these approaches are frequently developed specifically for research purposes, although they were initially commercially available technologies.

Andreadis et al. considered collaborative CAD activities through the use of software in the design process [20]. Collaborative CAD could involve a number of designers that are spread out geographically but use the same type of CAD software (version 2025 25.0) to maintain the consistency of the product data. This will lead to inefficiencies due to the tendency of individual designers to purchase and use their own local copy of the CAD software. Therefore, this research proposed a CAD architecture using cloud computing that is designed such that multiple designers can use a centralized CAD software with the help of communally used application servers, databases, and graphic processing units (GPUs).

On the other hand, Martinez-Maldonado et al. evaluated the collaborative design process from the perspective of the use of hardware, tools, and facilities to facilitate the design process [21]. To this end, they developed a studio containing dedicated digital devices for collaborative design, such as PCs, special tablets that can be projected onto the studio walls, and even a digital touch table that can be used together simultaneously by a group of designers. Although this solution has been proven to be effective for the formal instructional teaching of design theory, it nevertheless is an expensive solution and limits the collaborative process to designers that are located in the same geographical space.

Meanwhile, Kaya et al. concluded that research in collaborative CAD frequently developed prototype software that is complicated to use and expensive to implement [22]. As such, their research aimed to develop a tabletop-based collaborative CAD system that could be used to generate various models with low details. Collaboration is achieved with a number of designers using the same table to come up with a number of initial solutions. The model that is judged to be the best can then be exported as a CAD metafile and developed further into a detailed design using the appropriate CAD software.

One of the difficulties in collaborative design is in communicating design intention between one designer to another designer. The design intent can be defined as the knowledge of design variables (purpose of design, design constraints, alternative solutions, evolution of solutions, design guidelines, manufacturing instructions, manufacturing standards) that are implicitly stored in structural, practical and semantical associations between geometric, material, dimensional, and textual entities that are represented in a CAD system [23]. Good communication of the design intent should enable an increase in the efficiency of collaborative design.

Communicating design intent can be achieved in collaborative design using feature-based CAD by automating the documentation process of the design intent behind a modeled feature through the use of semantic network [24]. Therefore, CAD models generated through the system are guaranteed to have a design intent document that can be used in other design activities.

Other considerations of collaborative activities can arise when the activity involves actors from different disciplines or roles within the organization. The difficulties are also numerous, such as in organizing the design process or forwarding information from other roles that may have an impact on the design. Various studies have shown different approaches to these problems, such as by coordinating design activities across multidisciplinary team members [25], engaging in collaborative parametric design [26], or building a cross-role information system for the design process [27]. Xu et al. [28] used large language model (LLM)-enabled generative artificial intelligence (AI) as an agent that can collaborate with human stakeholders and functions as a decision maker in the design process.

Much research in conceptual CAD is carried out using different approaches and through proposing different solutions for increasing the efficiency of conceptual CAD. This is to be expected as there are many definitions regarding conceptual design and the precise activities within it. Wang et al. concluded that CAD systems have not been able to support conceptual CAD activities [29]. The same conclusion is also given by Vuletic et al. in a very recent study that evaluated other research on computer-based conceptual design [2]. They identified 16 prototype computer-based CAD systems regarding conceptual design that have been developed since the year 2000, but they have also concluded that there is no widespread approach that has been widely adopted by industry and as such, research in this field is still open to significant developments that can be accepted by industry practitioners. This suggests that conceptual CAD is still an open field for research and its development is a complex problem that can be approached from different angles.

Komoto and Tomiyama developed a conceptual CAD system for electromechanical products using a product function decomposition approach [30]. The system is equipped with a modeler that can be used to generate a metamodel of the product, consisting of functions, physical features, entities, and the connection between all these data at a system level. The data are stored in a knowledge base that can be used by a designer when designing a new product. The CAD system also contains a geometric modeler with primitive shapes that can be used to produce a skeletal model of the product. Noon et al. developed a conceptual CAD for designing large vehicles (helicopter, airplane, ship, etc.) [31]. The system utilizes primitive shapes and shapes from previous designs in a 3D modeler that can represent the overall construct of the vehicle. The system also incorporates VR technology that is used to review the product model. This research was conducted by defining conceptual design as the rapid modeling of shapes and forms without concern for the details of the model as these will be addressed in the detail design phase. Fu et al. developed a computer-aided system combining the Function–Behavior–Structure (FBS) design approach to obtain feasible principal solutions with the technique for order of preference by similarity to an ideal solution (TOPSIS) to obtain the optimal conceptual scheme (CS) [32].

Other research in conceptual CAD has focused on the generation of the product concept itself. Becattini et al. developed a computer-assisted system based on the TRIZ methodology that aims to help designers in generating product ideas [33]. The system will guide users using a dialog interface step by step through the TRIZ methodology to come up with innovative ideas. On the other hand, Du et al. developed a collaborative conceptual design system through software that can be used to systematically share product ideas [34]. Different users will be able to solicit their ideas to solve a design problem and the developed system will help to systematically organize and display those ideas.

Peng et al. developed a method to capture and formalize knowledge that is generated when designers collaborate in the design of a product [35]. The captured knowledge will then be available for use in other design activities as an input for the embodiment design phase. Designers from different disciplines and various roles are able to use the system to add their own knowledge into the system or to procure other knowledge relevant to the design problems that they are facing.

Pokojski et al. developed a framework for knowledge acquisition in conceptual design [36]. The framework can be implemented during the design activity, either for individual design or collaborative design. The implementation of the framework can be achieved using a multimedia-type database (used for storing texts, drawings, videos, 3D models, etc.) and with an interface that can be used to display the various media, such that designers will be able to use the collected knowledge as a reference to solve the design problem.

Khan and Tuncer researched other aspects of conceptual design using 3D CADs, that involves evaluating the match between a conventional feature-based 3D modeler and the needs of conceptual design that emphasizes speed and flexibility in visually describing ideas [37]. To that end, they developed gestures and voice commands that can be used to operate a 3D modeler as an alternative control scheme that they deem to be more natural compared to the usual mouse and keyboard controls.

A recent approach in conceptual design incorporates generative AI and LLM to help designers in designing new products. Advances in AI have enabled design prompts in natural language to be converted into images and, as such, they can help in translating the voice of the customer or design tasks straight into design concepts [28,38]. Although these images are not yet ready to be used in the production pipeline, nevertheless, the approach represents a very interesting prospect for increasing design efficiency.

To the best of our knowledge, research on creative CAD is mostly focused on creating databases containing physical phenomena as a source of ideas for designers when they are searching for physical structures to realize product functions [3,35,39]. On the other hand, research regarding CAD and human cognitive faculties are focused on trying to describe the correlation between the use of CAD and the cognitive load that is generated from the activity [40,41].

At the early design phase, the details of the design that are needed to make decisions regarding the quality of the design are still scarce. General assessment parameters, such as production costs, limitations and difficulties in full production, desirable quality levels, etc., still cannot be precisely measured. Therefore, decisions regarding the design at this phase will involve a lot of subjective evaluations from the designers based on their knowledge and experience of past design cases.

Studies in past research have discussed some methods to evaluate designs at the conceptual and embodiment design phase. Liu and Lu introduced a novel conceptual design methodology, Analysis Synthesis Alteration (ASA), that enables the designer to come up with alternative solutions that will then be filtered into one final solution for the designer [42]. In the research, all ideas for alternative solutions, either generated from the ASA method or the conventional brainstorming method, were rated by a team of 36 independent assessors regarding their functionality, usability, feasibility, affordability, and novelty. However, the details of the assessment are not provided.

Liu and Lu also proposed a conceptual design methodology termed Innovative Design Thinking (IDT) [43]. The research compared the proposed method with other known methods such as Analytical Target Cascading (ATC) and axiomatic design theory (ADT) by assessing ideas generated from each method based on the metric of novelty and quality, utilizing the assessment procedure developed by Shah et al. [44]. The same assessment procedure was also used in a follow-up study, whereby they compared the quality of the ideas generated from the IDT methodology combined with a crowdsourcing design framework (CDF) [45]. However, the research again did not specify the quality aspect that was used to assess the ideas.

Shah and Vargas-Hernandez proposed a method to assess the effectiveness of formal methodologies in the ideation process to generate design ideas for engineering design cases [46]. To assess the effectiveness of a given method, all the ideas generated are objectively rated using four criteria: novelty, variety, quality, and quantity. The novelty and quality criteria are measured for all of the ideas, whereas the variety and quantity criteria are measured for groups of ideas generated from a particular ideation method. All the criteria are calculated using a quantitative equation such that the assessment can be categorized as being objective, although the subjectiveness of the judgment is still shown through the weight given by the assessor on the various aspects of measurement.

Liu and Lu divided the IDT method mentioned above into specific steps and gave an example of its application for an engineering design problem [45]. In this research, the process of concept selection from several different early concepts at the conceptual design phase is framed as the problem of choosing a concept with the greatest physical certainty of being implemented. To that end, the probability of success for every concept is estimated and the concept with the highest estimation of success is chosen. However, the research does not elaborate further on the method of establishing the estimates and the people responsible for coming up with the estimates.

For evaluating the embodiment designs, several studies show that the approach taken involves evaluating the designs based on quality parameters that will become key parameters during the production process, such as focusing on how a geometric change in the design will affect the functional characteristics of the product [47], or focusing on evaluating the cost of production through knowledge formalization of the manufacturing process [48].

On the other hand, de Silva and Behbahani decided on several specific criteria that can be used to evaluate conceptual designs of mechatronic products [49], such as the following:

- The ability to fulfill the given product functions;
- Reliability (the chance of product failure);
- Intelligence (the ability of the product to make decisions according to its given functions);
- Compatibility (between product components, between software and internet network, between product and environment, etc.);
- The ease of use;
- Energy efficiency;
- Production costs.

For routine designs, the use of a database and knowledge management system have been proven to assist designers in the conceptual design phase. Chin and Wong gave designers questions about the product requirements and the answers were processed through a logical heuristic developed to choose the best design [50]. This is performed by matching the product requirements with the performance of the product, quantitatively as well as qualitatively, for every given design. Mukherjee and Liu developed a system to translate product requirements stated using simple language into sketch abstractions [51]. These sketch abstractions could then be matched with parts generated from previous design activities. The drawback of such methods is that they require an in-depth estimation of the product performance; as such, they are unsuitable for the design of new products or complex products with equally complex functions.

If the designer has sufficient knowledge about the working principles for a given design, simulation techniques can also be used to describe the level of performance of a given design. Clayton et al. used a virtual product model and object interpretation to document and illustrate the design intent for a particular product feature [52]. The design interpretation can be used to evaluate the design concept by checking it against the user requirements. Delgado-Maciel et al. used a system dynamics approach, to simulate the design performance, combined with the TRIZ approach, to redesign the underperforming parts of the concept solution [53]. Weyrich et al. also used a simulation approach by defining modules that can be combined to describe certain design solutions [54].

Chami and Bruel developed a methodology for evaluating integrated conceptual design for mechatronics systems using the SysML modeling language [55]. The approach aimed to automate the majority of the design process by modeling the product requirements and finding the appropriate product configuration for the given requirements. The approach aimed to combine the principles of knowledge management with the flexibility of the simulation approach by using a configurable modeling language to widen the scope of the knowledge base that was currently being used. Remarkable effort is needed to validate the association between the product requirements, possible solution configurations, and the simulated product performance for a given solution configuration.

On the other hand, Moulianitis et al. used an index to evaluate mechatronic products considering several aspects, such as configurability, adaptability, interaction ability, dependability, motion ability, perception ability, and decisional ability [56]. Each aspect of an alternative design is evaluated using the given index and the design with the greatest evaluation score is considered to be the best design.

Akay et al. used interval type-2 fuzzy information axioms to bridge the quantitative and qualitative evaluation of designs [57]. Each design is evaluated on how well it fulfills the product requirements, in which the evaluation is conducted using simple language, but the result is transformed using a fuzzy set to come up with a quantitative assessment. Coutourier and Imoussaten proposed another qualitative assessment of designs by evaluating the design performance using criteria derived from the design requirements [58]. Jing et al. also came up with ways to evaluate conceptual designs by translating simple language evaluations into quantitative evaluations by using different methods, with a special focus on the uncertainties in evaluation semantics such as the subjectivity, randomness, and heterogeneity [59,60].

Liu et al. proposed a qualitative design evaluation method through the radicality of the design compared with other known solutions of the problem at hand [61]. The approach is very suitable for new product design, especially when novelty is considered crucial for the product. This research was partially based on another study, which proposed a method to measure the effectiveness of ideation methods, including a method to evaluate designs based on their novelty and quality [46]. Another research approach is also focused on new product development, where a statistical analysis is proposed to ascertain whether a design inspired from 'distant' sources of inspiration from previously known solutions has an inherent advantage over a design inspired by 'close' sources of inspiration from previously known solutions [62].

Table 1 highlights some characteristics of the abovementioned research, mainly through the conceptual and collaborative design lens. It can be seen that research that simultaneously concerns collaborative and conceptual design has employed various approaches to handle the problem. It is our conclusion that the highlighted studies have not been able to replicate the traditional 'one-room environment' for exchanging design ideas between a team of designers, although they have proposed many ways to improve the efficiency of the design process.

Table 1. Selected research on conceptual and collaborative design.

Aspect	**Komoto and Tomiyama [30]**	**Liu and Lu [43]**	**Eltaief et al. [10]**	**Kaya et al. [22]**	**Lv et al. [12]**	**Fu et al. [32]**	**Wang et al. [25]**	**Xu et al. [28]**
Collaborative Activity	Non-Collaborative	Non-Collaborative	Coordinative	Cooperative	Cooperative	Non-Collaborative	Coordinative	Cooperative
Collaborative Method	-	-	(1)	(2)	(3)	-	(4)	(5)
Conceptual Modeling	Yes	Yes	No	Yes	No	Yes	Yes	Yes
3D Modeling	Yes	No	Yes	No	Yes	No	No	Yes
Additional Technology	-	-	-	(6)	-	-	-	(7)

(1) Assembly change propagation based on part modifications. (2) Simultaneous low-fidelity prototype creation in a tabletop environment. (3) Cooperative CAD environment with selective undo. (4) Multidiscipline design model in Extended Design Structure Matrix. (5) Agent-Based Human–Machine Collaboration; Mixed Reality-based design review. (6) Motion sensor cameras and projector. (7) Generative AI. Mixed Reality.

3. CAD-Based Collaborative Conceptual Design Model

3.1. Principles of CAD Framework Development

As stated before, the proposed CAD framework is specifically developed to adhere to the principles of the four Cs in CAD. In this section, it will be explained how the principles are applied to the development of the CAD framework, where the principles can be further translated into requirements for the CAD framework and hence determine the subsequent workflow for the usage of the CAD software itself. Parts of the subsequent explanation have been mentioned in their preliminary form in our previous publication and are mentioned again here to illustrate a complete picture of the CAD framework development [63].

It can be seen that the biggest advantage of a CAD system with the four C characteristics is its use in the collaborative process of the early design phases. Designers need their creativity to come up with solutions during the conceptual–embodiment design phase, and the traditional collaborative design process, where a group of designers exchange design ideas in a single room, is becoming more impractical as design time constraints are becoming stricter and technological innovations already enable organizations to hire qualified designers located in separated geographical areas. Hence, there is a need to specifically design a novel CAD framework that should be developed based on human cognitive processes to help alleviate the mental stress of designers in the hope of shortening the design process duration.

Although the proposed CAD framework in theory can be applied to any engineering design problem, in this research, we will limit the CAD framework's application to mechanical and electromechanical product design, as one of the popular use cases of the term CAD refers to the design of such products. This in turn will help us to illustrate the workflow of the proposed CAD framework due to the familiarity of the use case.

Organizationally, the proposed CAD framework is intended to be used by a group of designers already tasked with developing a product with known intended functionality, that is, after the brief of the customers is collected and ready to be translated into product functions. Once again, for the sake of simplicity, in this research, the group of designers are assumed to have come from a single organization and there is no hierarchy between the involved designers. If the involved designers are from different organizations, then another level of complexity in the framework will arise due to the need to keep confidential design data separate between the involved parties and the differences in organizational policies or technological CAD infrastructure between the organizations. It can be seen from the workflow explanation in the preceding section that if the workflow is followed closely, then important decisions regarding the design that must be made will be decided organically, assuming that the designers are able to come to a consensus in several areas.

Lastly, it is assumed that the involved designers are geographically separated, as mentioned before, but that they all have the same level of expertise in product design and the use of CAD software. The proposed CAD framework can then be prioritized for asynchronous collaborative design because time differences due to geographical separation will further complicate practical synchronous collaborations. The designers' familiarity with several design methodologies is required as parts of several design methodologies are taken as a base for the proposed CAD framework, and they shall be noted explicitly in the preceding sections.

The cognitive theory that underlies the development of the proposed CAD framework is the Coevolution Design Theory [64]. The Coevolution Design Theory states that in design activities, designers are constantly defining and exploring two dimensions, namely, a problem space and a solution space. The problem space is the problem that needs to be solved, and the solution space is all the possible alternatives that can be used to solve the given problem. During the design activity, as the designer continues to iterate their solution, a modification to the problem usually arises, i.e., a new unforeseen sub-problem could arise, aspects of the problems should be further adjusted with the data obtained from the temporary solution, etc. All of these will encourage the designers to redefine the problem space itself which in turn will direct the designer to explore other solutions that will fit with the new problem. As such, both the problem space and the solution space will 'evolve' during the design activity. Figure 1 shows the model of the Coevolution Design Theory.

Further research [65,66] has shown that the Coevolution Design Theory is adequate for describing the cognitive mental workload that is associated with design activities. Furthermore, it has also been shown that the Coevolution Theory can also explain design activities conducted in a group setting [67]. CAD software is focused on giving designers the tools to explore and elaborate the solution space, but to the best of our knowledge, there is no explicit CAD software that has provided an integrated environment where designers are free to manipulate and redefine both the problem space and the solution space.

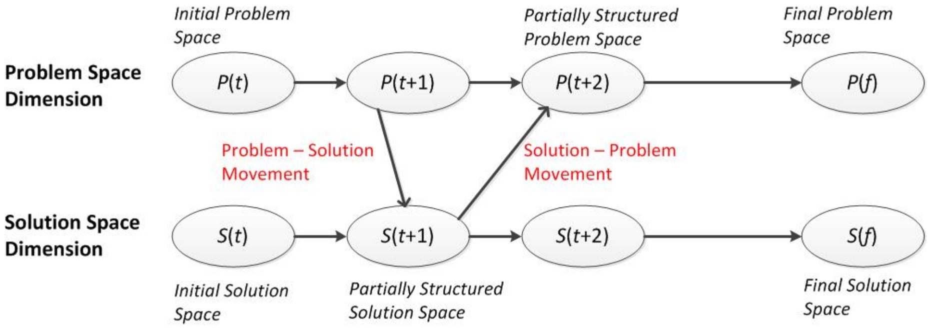

Figure 1. Coevolutionary Cognitive Design Theory, adapted from Dorst and Cross [66].

Design activities, especially in engineering product design, can also be characterized as distinct phases, marked by the different tasks that the designer will complete during each phase [68]. Chen et al. [15] stated that the engineering design phase can be distinguished as follows:

- Functional Design, where designers should define product functions based on the gathered requirements.
- Conceptual design, where designers should find basic engineering structures that are able to deliver the desired functions.
- Embodiment design, where designers should map the basic engineering structures into realizable sub-modules, components, and interfaces.
- Detail design, where designers should elaborate on each component until they have the sufficient level of detail to be manufactured.
- Engineering Analysis, where designers should further experiment with the designed product to see if it could fulfill the intended functions.

We have chosen to adopt this distinction of the design phases in this research because it is broadly in line with the one stated by Pahl et al. [68], namely, the task clarification–conceptual–embodiment–detail design phase, that has been widely adopted in engineering design standards in Europe. However, the chosen definition creates a finer distinction between the phases while simultaneously simplifying the details within the phases. We feel that this distinction is needed, as one of the goals of the CAD framework is to simplify the complexity regarding the early design phase, which has contributed as one of the reasons why there is difficulty in creating computer-aided tools to help in the early design phase.

The proposed CAD framework is likewise focused on supporting the conceptual–embodiment design phase, a design phase that still lacks CAD support compared to the detail design phase. During the conceptual–embodiment design phase, designers are looking for the connection between functions and structures, as such basic parametric shape modeling that is widely used in CAD today is also sufficient for representing the engineering structures and product layouts that are produced from this phase. Applying the Coevolution Design Theory to the conceptual–embodiment design phase, it can be seen that the problem space is equivalent to the list of functions that are generated from the Functional Design Phase, and that the solution space is equivalent to the product model, which will realize the product function. The proposed CAD framework will give designers the capability to define and edit the function list for the designed product and to create a 3D model to represent the product concept.

The proposed CAD framework is also developed to be used in collaborative design activities. In the conceptual–embodiment design phase, cooperative activities have the potential to create more value in the design process compared to coordinative activities. Coordinative design is more suited to the detail design phase, where designers already have a sense of the end product that they will end up designing, and as such, sharing the design workload becomes an efficient way to design a product in a timely manner. On the other hand, in the conceptual–embodiment design phase, where there are many solution alternatives, designers will also have freedom to explore the solution space by using cooperative design to design all the parts of the product together from the beginning.

As designers explore the solution space, each designer could have more than one possible solution for the design problem that is given. In the conceptual–embodiment design phase, this ‘divergence’ of a solution is needed so that an exhaustive search in the solution space can be performed; however, as the real evaluation of a design comes at a later phase of the design activity, there is a need for a method for comparing and choosing between several conceptual designs put forth by the designer that will ‘converge’ the possible solutions into one design that will be further developed in the later design phases, as depicted in Figure 2. The proposed CAD framework will incorporate a novel method for the purpose of the comparison of conceptual designs, which will be further elaborated on in the next section.

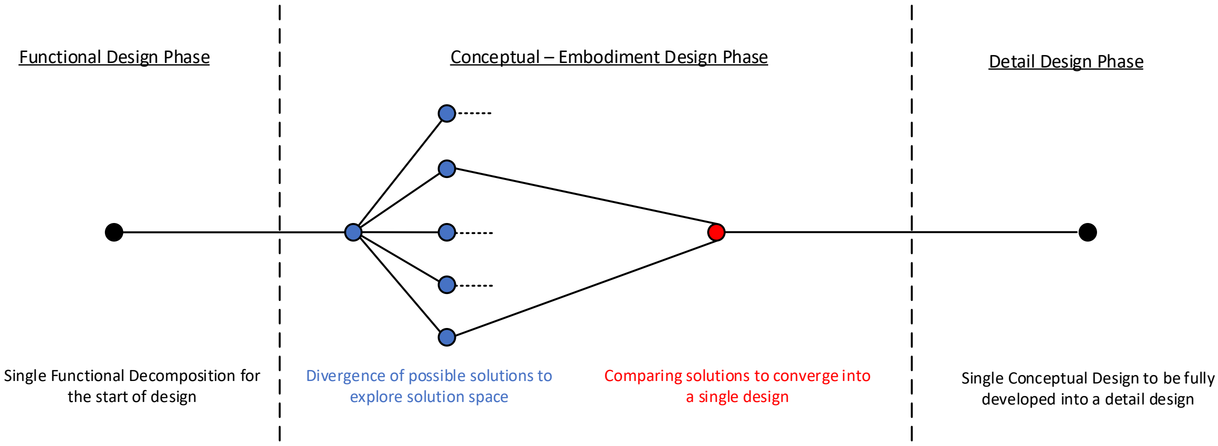

Figure 2. Divergence and convergence of design solutions throughout the design activity.

Regarding the principle of creativity, the proposed CAD framework will try to push the creativity of the designers through the collaborative process itself, that is, through the exchange of ideas between designers during the design process. As mentioned before, the proposed CAD framework will be used to translate a list of functions into engineering structures. Therefore, as the users continue to use the proposed CAD framework, it is possible to create a database containing information on possible engineering solutions for each product’s functions that must be realized in the design. The database could also then be used by other designers to search for possible solutions if they encounter similar problems in the future.

In summary, to realize the four C principles of CAD, the proposed CAD framework will consist of four primary modules that will work together in assisting designers during the conceptual–embodiment design phase. These modules are shown in Figure 3, and they consist of a Functional List Module, Shape Modeling Module, Database Module, and Design Evaluation Module. A brief explanation for the modules is as follows:

The Functional List Module is the ‘problem space’ for the design process. Regarding the conceptual–embodiment design phase, this module corresponds to the functions that will be translated into physical structures. Here, all designers that are involved in the design process will be able to define and edit the list of functions that will be realized by the designed product. A simple functional decomposition diagram can be used to represent the list of functions in a more concise manner. As an illustration, a collaborative online chart maker program can be used to realize this function.

The Shape Modeling Module is the ‘solution space’ for the design process. Regarding the conceptual–embodiment design phase, this module corresponds to the physical structures and their configuration to realize the given functions. Here, each designer is given their own space to create a model of the engineering structures and their configuration. As an illustration, a simple 3D modeler can be used to fulfill the function of this module.

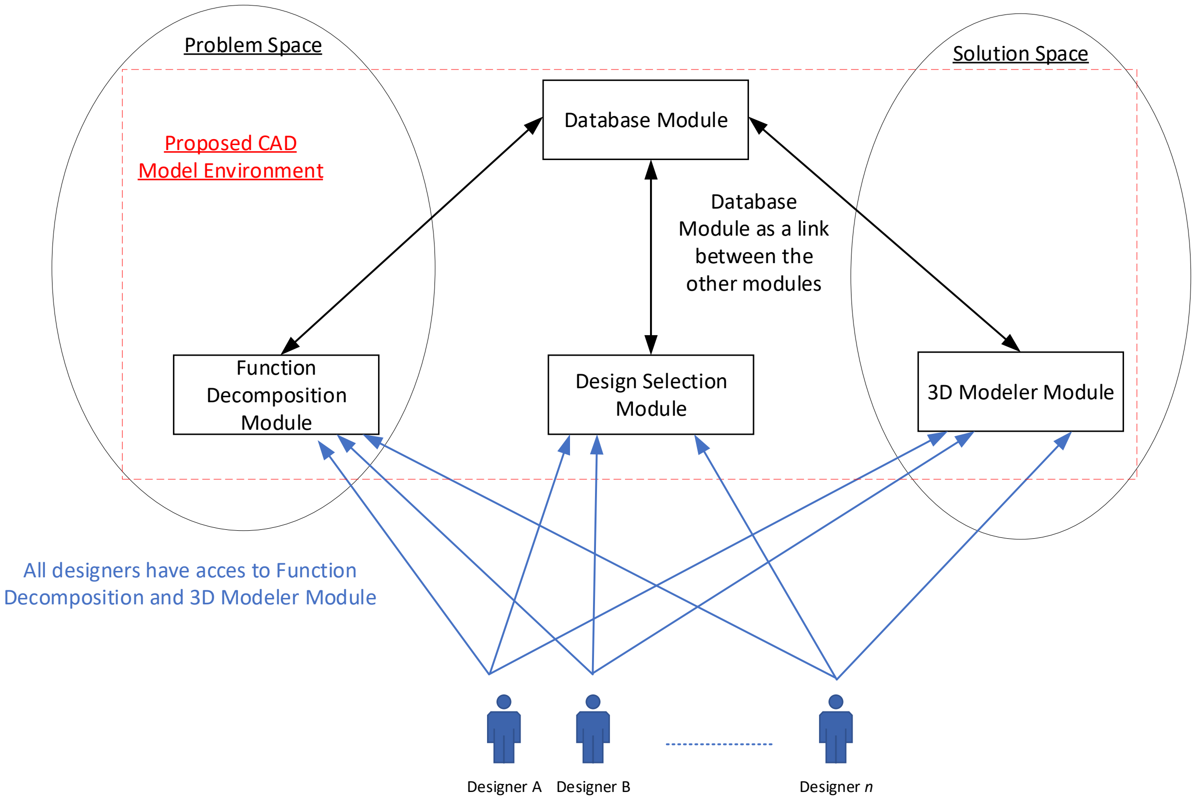

Figure 3. Proposed CAD framework and its component modules.

The Database Module is the connector between the other modules. It is tasked with linking the CAD models with the given functions so that they can be recalled in the future and as a guide in the design process itself. It is also used to track all the versions resulting from the changes in the 'problem space' and the 'solution space', that is, the functional decomposition and the product models, as they 'evolve' during the design process. As an illustration, the functions of this module can be realized using a basic database program, as they are intended primarily to only store information regarding the 3D model and the functional diagram and not the 3D model itself. The list of functions from the functional diagram and the file name of the 3D models are first inputted into the database, and then a particular function is paired with one or more 3D models that is intended to fulfill that particular function. This arrangement will help to reduce the need for file storage, as the 3D models created by each designer are stored in each designer's respective file repository. Although having a database of the design implies that it can be accessed by the designer to help in the conceptual design process, this functionality has not yet been considered at this stage of our research, and it will be further added in the future. Rather, at the moment, this module is primarily used to link the information in the design process, as explained before. The designers will interact with the other modules, while in the background, the Database Module will extract information from the other modules and perform the necessary actions to support the workflow. This will be explained in detail in the following sections.

Due to the collaborative nature of the proposed CAD framework, there is a need for a Design Evaluation Module. This module will be able to compare and choose the best conceptual–embodiment design out of possible solutions using the comparison method, that will be further elaborated on in the subsequent section.

All the modules will then need to be combined to create an integrated CAD system for the collaborative early design process. Realizing the integrated system requires a specialized program to seamlessly connect the disparate modules into a collaborative workflow that will be detailed in the preceding section. As an illustration, the program must be able to handle the 'background' work that enables the workflow to run smoothly, such as allowing the designers to log into the system, handling the data communication between the involved designers, giving prompts and updates according to the collaboration workflow, and also helping in comparing each designer's design using automatic updates.

3.2. *Workflow*

In this chapter, further elaboration will be given on the workflow when using the proposed CAD framework. As the system is used in the conceptual–embodiment design phase instead of the detail design phase, and it incorporates a functional decomposition module that is usually kept in a separate environment, it is necessary to illustrate the workflow of the proposed CAD framework to understand how it will be used. An overview of the proposed workflow is shown in Figure 4, and the detailed explanation for the depicted workflow is as follows.

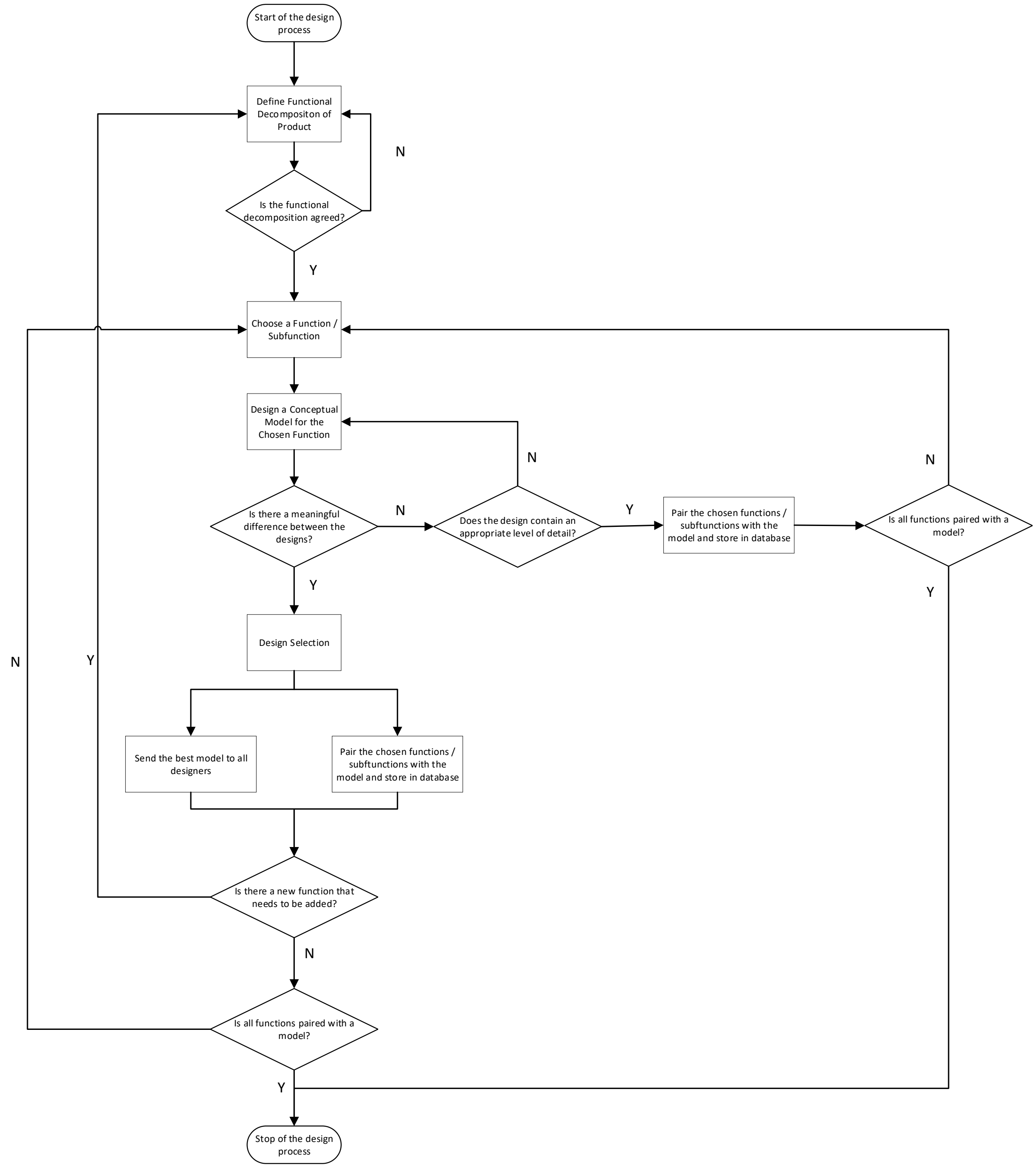

Figure 4. Flow diagram of the proposed workflow.

The design process should start with the functional decomposition of the product. The functional decomposition in the CAD program will be represented by a functional decomposition diagram that can be edited by all the designers involved in the design process. This is performed in the functional decomposition module as mentioned above. After all the designers have agreed on the functional decomposition, the next step of the design process can be started.

The designers should then choose a particular function or a subfunction from the functional decomposition diagram to start the design, and then each designer is free to create an object model that can realize that particular function, i.e., a structure that will be able to perform the associated function in the product. This is completed in the Shape Modeling Module.

As mentioned before, each designer will have their own space in the Shape Modeling Module, such that each design is independent. Instead of running a concurrent modeling section in a 3D modeler software, the separate workspace is realized by giving each designer a 3D modeler software that is run independently by each designer in their own space. In this way, every designer will have the freedom to put forward the design that they feel will correspond best with the chosen function and they should expand the design to a sufficient level of detail that will show the meaningful differences between each design. The CAD program will help in comparing the designs by showing the most recent design results from the other designers whenever a designer updates their own design. If the designers happen to arrive at similar solutions for a given function (a similar structure without a significant difference), the designers should incorporate another function in the existing embodiment design and develop the product structure accordingly until a meaningful difference between the designs can be found, and the different designs should be converged through the selection of the best design. This implies that direct communication between the designers can be kept to a minimum but at the same time, each designer is aware of the progress of the other designers and this in turn is hoped to further spark the creativity of the involved designers. The lack of direct communication also encourages asynchronous collaborative design because the involved designers do not need to make an appointment for a modeling session.

It is then up to the designers to choose when to initiate a comparison between the designs by using the CAD program. After being prompted to start the comparison, the CAD program will utilize the design comparison algorithm detailed in the next section to guide the designers in choosing the best design for the given function. The best design will then be copied and sent to each designer so that each designer will have the same CAD model file that can be used as the basis for the further development of the design.

At this point, the Database Module will note the pairing of the function with the product model and keep the association in a database. The design process will then proceed, with the designers agreeing upon another function or subfunction to develop, and then designing the associated structure, initiating the design comparison, and so on. The design process stops when all the functions listed in the functional decomposition have been paired with a product structure.

According to the Coevolution Design Theory, the list of functions that represent the conceptual design (problem space) and the product model that represents the embodiment design (solution space) will change as the design process proceeds. Therefore, the CAD program will enable the designers to update both the functional decomposition and the product models associated with that particular design. The changes to the functional decomposition should be agreed upon by all the designers and each designer will also be able to freely update their product models.

It is then up to the Database Module of the CAD program to help keep track of all the changes such that the whole design process can proceed accordingly.

Figure 5 shows an illustration of the workflow for the proposed CAD framework, starting from choosing a base function to the comparison of the designs and also showing the coevolution of the solutions and the function decomposition. The blue line indicates the passage of time during the design process, and the figure conveys that, as the design progresses, both the functional diagram (in the problem space of the Coevolution Design Theory) and the 3D model (in the solution space of the Coevolution Design Theory) will keep evolving. In the solution space, each designer involved in the process is able to design their own solution independently and then compare them to choose the best solution. The CAD framework aims to help designers in 'hopping' between the two spaces by combining each space and the respective design tasks in them into an integrated CAD system.

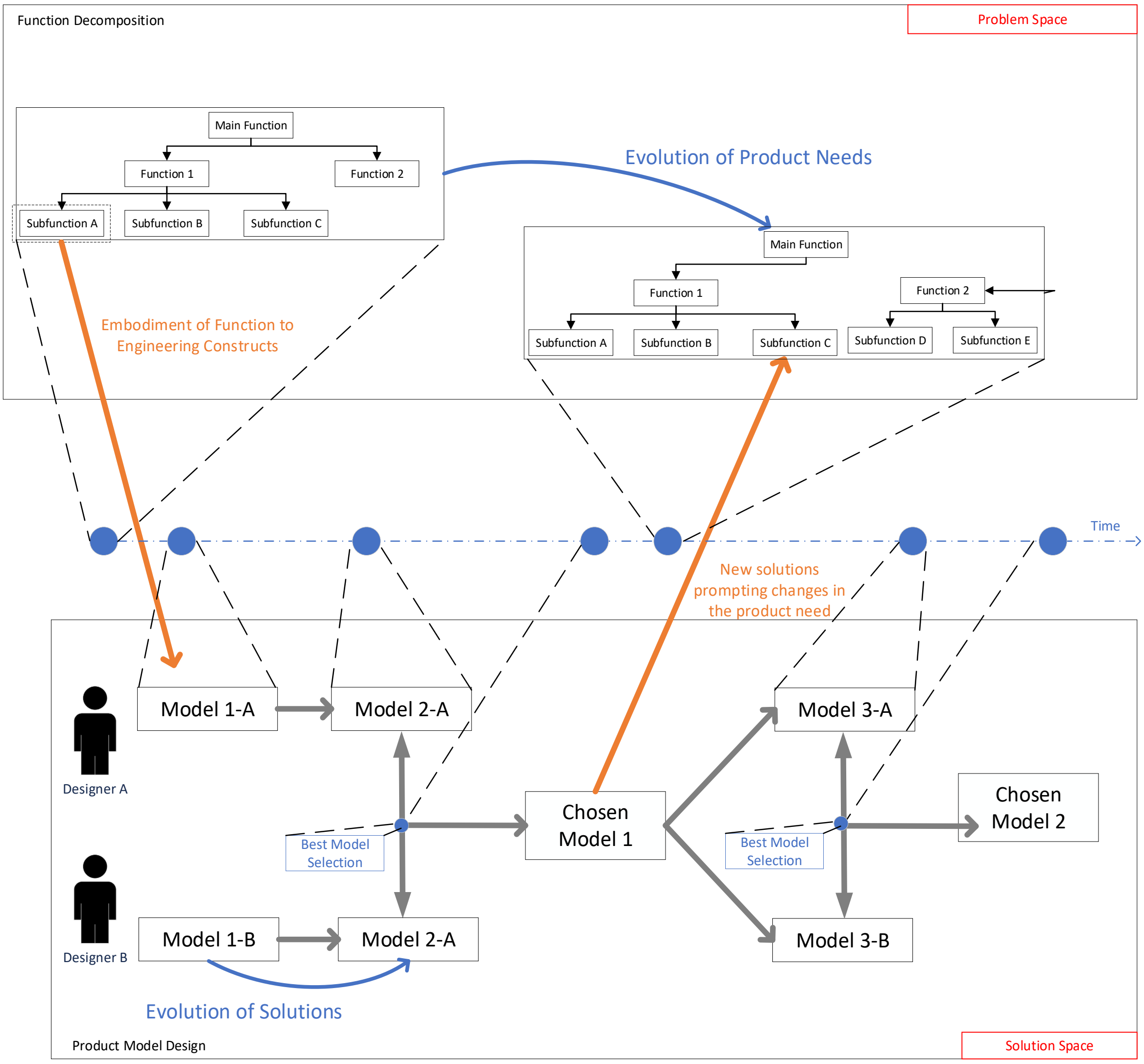

Figure 5. Overview of the proposed CAD framework workflow.

3.3. Conceptual Design Comparison

The conceptual design comparison will be performed using a method based on the Hurwicz criterion for decision making under uncertainty conditions [69]. As such, the selection of the conceptual designs is also viewed as a decision making problem under uncertainty conditions, i.e., for every design, there is uncertainty around whether the design will be able to perform according to the customer's needs. Therefore, a design that is deemed more probable to achieve the required design parameters according to the customer's needs will then be able to provide more payoff value.

The conceptual design comparison is also closely linked to a popular design methodology, the House of Quality (HoQ) method [70], where during the early design stage, designers are tasked with estimating the target value of certain technical attributes of the product. Therefore, it is reasonable to expect designers to be able to estimate a range of values (minimum and maximum values) for a set of corresponding attributes that will be possessed by the final product. In many engineering applications, although target values can be stated as intervals, in reality, many such values are actually unbounded, for example, the number of passengers that a mass rapid transport system can transport at once (the more passengers, the better), or the minimum weight of a camping bag (the less weight, the better). After the payoffs for all the technical criteria have been calculated, the payoffs will then be aggregated. The aggregation process itself is also developed from the HoQ method, where, traditionally, it is preferable if the weight for each criterion is stated as a percentage, such that when all the weights are aggregated, they add up to 100.

The following explanation for the design selection method as shown in this chapter is taken from our previous publication [71]. Using the Hurwicz criterion, the decision maker is able to project their confidence (i.e., optimism or pessimism) in whether a decision will meet its intended outcome. This criterion can be stated as

$$H = \alpha \max(x) + (1-\alpha)\min(x), \quad (1)$$

where H is the Hurwicz criterion payoff, α is the coefficient of optimism that measures the decision maker's optimism ($0 \leq \alpha \leq 1$), max(x) is the maximum payoff of action x, and min(x) is the minimum payoff of action x. Consequently, if x is the action of choosing a certain conceptual design x, then for each technical criterion i, the payoff of choosing design x can be indicated by

$$H_{xi} = \alpha \max_i(x) + (1-\alpha)\min_i(x) \quad (2)$$

where H_{xi} is the Hurwicz payoff of choosing design x for technical criterion i, α is the coefficient of optimism that measures the decision maker's optimism regarding the ability of design x to achieve the target value for technical criterion i ($0 \leq \alpha \leq 1$), $\max_i(x)$ is the target value for technical criterion i, and $\min_i(x)$ is the minimum performance value achievable for technical criterion i.

As stated before, normalization of the payoffs is performed using the weight of each criterion, such that in the full pessimistic condition (α = 0), the normalized payoff for criterion i equals zero, and in the full optimistic condition (α = 1), the normalized payoff for each criterion i is equal to the maximum weight assigned to that criterion. For target values that are approached from the bottom up (a higher target value is better), the normalized payoff can be written as

$$N_{xi} = w_i[H_{xi} - \min_i(x)]/[\max_i(x) - \min_i(x)] \quad (3)$$

where N_{xi} is the normalized payoff of choosing design x for technical criterion i, H_{xi} is the Hurwicz payoff of choosing design x for technical criterion i, $\max_i(x)$ and $\min_i(x)$ are the maximum and minimum performance value for technical criterion i, respectively, and w_i is the weight for criterion i. For target values that are approached from the top down (a lower target value is better), the normalized payoff can be written as

$$N_{xi} = w_i - (w_i[H_{xi} - \max_i(x)]/[\min_i(x) - \max_i(x)]) \quad (4)$$

where N_{xi} is the normalized payoff of choosing design x for technical criterion i, H_{xi} is the Hurwicz payoff of choosing design x for technical criterion i, $\max_i(x)$ and $\min_i(x)$ are the maximum and minimum performance value for technical criterion i, respectively, and w_i is the weight for criterion i. It should also be noted that for this type of value, $\max_i(x)$ is the lower number and $\min_i(x)$ is the higher number.

For each conceptual design, it is possible that the range of the operation between each design is different. In this case, after counting the Hurwicz payoff for each design, the value should be put into the same scale before normalization, with the minimum payoff set as the minimum achievable target value, which is the lowest number for bottom-up target values and the highest number for top-down target values. Figure 6 illustrates this principle. As such, for a more generalized case, Equations (3) and (4) can be expressed as

$$N_{xi} = w_i\left[H_{xi} - \min_i(x')\right] / \left[\max_i(x) - \min_i(x')\right] \tag{5}$$

$$N_{xi} = w_i - \left(w_i\left[H_{xi} - \max_i(x)\right] / \left[\min_i(x') - \max_i(x)\right]\right) \tag{6}$$

where x' is the design that has the minimum achievable target value of all the available designs for each i.

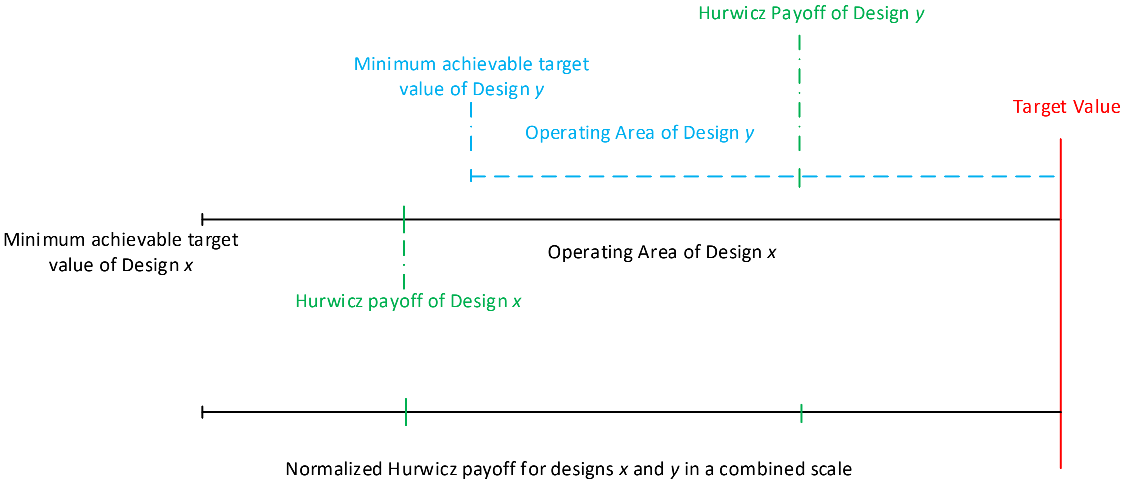

Figure 6. Combined payoff between two different operational ranges.

Our literature research has shown that much research in design selection also relies on objective evaluation during the conceptual–embodiment design phase. Our objective is to reduce the subjectiveness as much as possible, and that is why we came up with the approach of using the Hurwicz criterion to state the designer's confidence in whether the design will meet its intended function in terms of the objective technical criteria, although the weight of the criteria itself still needs to be decided subjectively by the designers. As this is a collaborative design procedure, the weights should be decided by consensus of the involved designers, although it is assumed that this can be achieved independently by the designers without guidance from the proposed CAD framework.

The CAD program described in this research aims to support the comparison process by prompting the designers to list the technical attributes of the product, inputting the appropriate weight and scale for each attribute, inputting the predicted maximum and minimum value for the attributes, inputting the Hurwicz value for every criterion, and then displaying the results. As this assessment method is used in a collaborative setting, each designer must evaluate all the available conceptual designs. This is performed to avoid bias for a particular design created by the same designer. Lastly, the final assessment score for each design will then be the average score of all the evaluations provided by the participating designers.

4. Case Study

This part will illustrate with a simple hypothetical case how the CAD framework can be used in a collaborative design activity, specifically, a detailed explanation of the comparison method developed for the framework. It should be noted that all the designs and numbers shown for the case study are generated for the purpose of validating the collaborative framework and not taken from an actual lab study involving real-life designers, although an actual experimental study to further explore the framework is already scheduled as of the writing of this paper. The product that is used as an example is a walking stick. The walking stick is a mechanically simple item that consists of several different parts. Since the number of parts itself is small and the function of each part is also simple, this case can perfectly illustrate the use of the collaborative CAD framework that is outlined in the previous sections. In this scenario, there are two designers involved in the design activity:

Designer A and Designer B. The number of designers is chosen to represent the simplest form of collaborative design, and scaling up the number of involved designers will not alter the steps of the framework; rather, it will increase the burden of communication to arrive at consensus. Each designer will then come up with different embodiment designs for the problem, termed Design X for the designs produced by Designer A and Design Y for the designs produced by Designer B. The preceding subsections will follow the workflow of the CAD framework explained previously.

4.1. Collecting Consumer Requirements

The design process should start with collecting consumer requirements for the product, which, in this case, is a walking stick. The collection of consumer requirements is performed outside of the scope of the CAD framework; as such, the requirements are used only as inputs for the CAD framework. The consumer requirements are usually stated in simple language as they are written or spoken directly by potential consumers. For this example, the requirements for the walking stick are as follows:

- Able to support one’s bodyweight.
- Safe to use.
- Easy to use.
- Comfortable to use.

4.2. Translating Consumer Requirements into Product Functions

In the next step, the consumer requirements are translated together by all the designers into hierarchical functions and subfunctions of the product. The CAD framework will be able to represent the functions and subfunctions using a functional diagram. The functional diagram is chosen because it can be used to represent complex products with many functions in a structured way. The diagram can also be easily manipulated by the Database Module, which ensures that all the objects in the diagram will be paired with one or more parts model during the design activity.

All designers that are involved in the design activity are given access to see and edit the functional diagram. The Database Module will also be responsible for tracking the various versions of the functional diagram to ensure the smooth flow of the design activity. When all the designers have agreed that there is no functions left that can be elaborated into subfunctions, then they are ready to commence the embodiment design activity.

In this example, the functional diagram for the walking stick can be seen in Figure 7. The consumer requirements are translated into four functions and subfunctions, which are as follows: supports the user’s bodyweight, directs the user’s bodyweight, prevents slipping, and is able to be moved easily. In the diagram below, the final functions and subfunctions are symbolized with a dashed box.

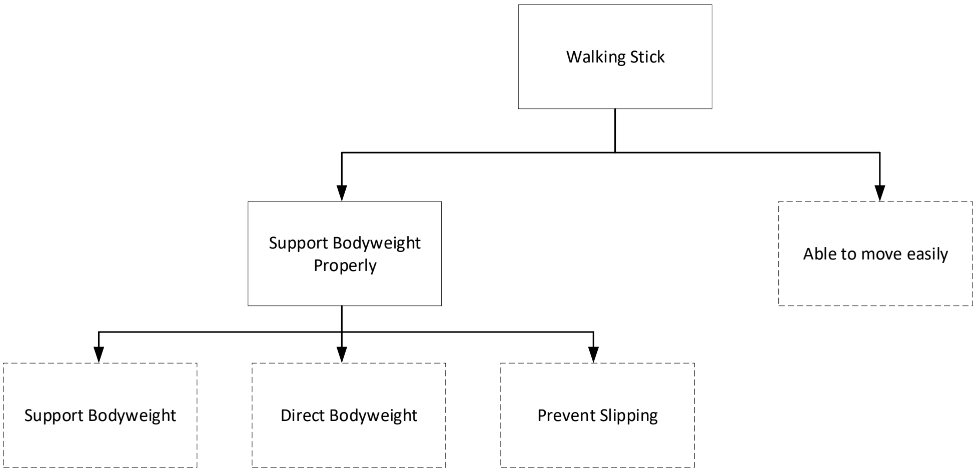

Figure 7. Functional diagram of walking stick.

4.3. Start of Embodiment Design Phase

At this time, the embodiment design phase is started by developing parts or subassemblies that will be able to fulfill the previously defined functional requirements. The designers are prompted to agree on one function or subfunction that will be developed first. During the design process, each designer is free to continue to develop embodiment designs for other functions according to their own preferences, until the comparison with the other designer has to be made.

As mentioned before in the Section 3.2, each designer is given their own workspace in the Shape Modeling Module such that they can create their own designs independently of one another. The CAD program will help the designers in comparing the design results by using prompts and updates to the other designers. Each time a designer saves a model and closes the CAD program, a notification update will be sent to the other designers in the design process, showing the latest completed model to all the other designers. In this way, comparisons can be made asynchronously and efficiently without too many burdens on data communications.

When one of the designers in the design activity has judged that there is a significant difference between the designs, the designer will use the CAD program to prompt a comparison between the designs so that the best design can be chosen as the base for subsequent developments.

In this example, Designer A and Designer B have agreed on the subfunction 'support bodyweight' as the starting point for the design. Each designer will then create a 3D model for the walking cane that is suitable for supporting the user's bodyweight. The designers created the designs shown in Figure 8. It can be inferred that both designers agree on a fairly similar design, consisting of a 'cane body', which enables the cane to support the user's bodyweight, and a 'cane handle', which enables the transfer of the user's bodyweight to the 'cane body' via the user's hand and thereby also fulfilling the subfunction of 'directing bodyweight'.

Figure 8. Design X (**left**) and Design Y (**right**) for 'cane body' and 'cane handle'.

At this point, it can be seen that the main difference between the two designs lies in the part 'cane handle'. Designer B considers the difference to be significant and prompts the design comparison phase from the Shape Modeling Module in the CAD program. At the same time, the Database Module is used to pair the functions with the designed parts, i.e., associating the 'direct bodyweight' subfunction with each of the 'cane handle' parts. These associations could also be searched for and explored in further design activities after they have been added to the database.

4.4. Design Comparison

The designs will be evaluated using the methods explained in the section above. The CAD program will take the functions defined in the functional diagram and prompt the designers to fill in the technical criteria, the importance of each technical criterion, and the target value for each technical criterion, and then filling in the expected range of the technical criterion for each of their own designs. The CAD program will also prompt the designers to mark each target value as a 'top-down' value or a 'bottom-up' value.

The definition of technical criteria and its importance weight are performed regularly in the House of Quality method; therefore, it is reasonable to assume that the designers will be able to do the same when using the CAD program. Although designers must come to a consensus about all the technical criteria and their importance, the actual process of coming to an agreement is currently out of the scope of this paper. The importance of each technical criterion should be valued between 1 and 9, with a value of 1 meaning that the technical criterion has very little correlation to the actualization of the product function, and a value of 9 meaning that the technical criterion has very strong correlation to the actualization of the product function.

Table 2 shows an example for the function list and the importance weight for the walking cane design example, while Table 3 shows an example for the minimum and maximum values (value range) for each technical criterion in both Design X and Design Y. The upward arrow in Table 2 indicates that the target value is a 'bottom-up' value and the downward arrow indicates that the target value is a 'top-down' value, while the percentage is calculated by normalizing the sum of all the importance weights for each technical criterion.

Table 2. Function and importance weight for technical criteria.

Function	**Technical Criteria**			
	Weight	**Vertical Length of Cane Body**	**Horizontal Length of Cane Handle**	**Weight Support**
Support Bodyweight	5	3	7	9
Direct Bodyweight	3	7	7	3
Prevent Slipping	9	1	5	1
Able to Move Easily	9	7	7	1
Total Weight	26	18	26	14
	31%	21%	31%	17%
Unit	Kg	cm	cm	Kg
Target Value	0.5 (↓)	120 (↓)	15 (↓)	150 (↑)

Table 3. Operational range for each design.

No	**Criterion**	**Design X**		**Design Y**	
		Min	**Max**	**Min**	**Max**
1	Weight (kg)	0.5	0.7	0.5	0.6
2	Length of Cane Body (cm)	120	121	120	121
3	Horizontal Length of Cane Handle (cm)	15	16	15	16
4	Weight Support (kg)	145	150	130	150

There are two situations where the design evaluation can be carried out. In the first situation, the evaluation is performed limited only to a single embodiment design which is connected to a limited set of functions or subfunctions. In this situation, the designers should only provide the technical criteria that relate to the design they wish to evaluate. For example, if the designers wish to only evaluate the embodiment design for the 'cane body' part, then the related subfunction can be limited to only the 'support bodyweight' function, with 'cane bodyweight', 'length of cane body', and 'weight support' as the related technical criteria. The selection of these criteria should consider the factors relevant to the product, in this case, for example, anthropometric considerations (translated into ‘cane dimensions’) and material strength (translated into ‘weight support’). The designers should have the knowledge to translate all the factors into the relevant technical criteria that are easy to measure objectively.

The second situation is the situation shown in this example, where the embodiment designs for several parts are evaluated simultaneously. This situation arises when the resulting designs contain similarities in several designed parts and also significant differences in other designed parts. The evaluation should be performed simultaneously when it is assumed that the different parts will interact with the similar parts during the realization of the given functions; hence, the design comparison should be performed for the whole design.

Sound judgment and good coordination from the designers are needed to ascertain which situation best applies to the given design activity. The CAD program will enable the designers to fill in the relevant technical criteria for each design comparison and to select the relevant product functions that should be evaluated for every embodiment design that is generated through the design activity.

The design evaluation will be performed using the Hurwicz payoff as explained in the previous section. Before the payoff calculation and aggregation can be performed, each designer is prompted by the CAD program to input their optimism coefficient for each design that is generated. The CAD program will then calculate and show the aggregate Hurwicz payoff value for each design, such that the designers can see which design is ranked best among all the generated designs. Table 4 shows an example of the coefficient of optimism of the designers for each criterion in each generated design, while Table 5 shows the aggregate Hurwicz payoff value for Design X and Design Y.

Table 4. Coefficient of optimism for Design X and Design Y.

	Technical Criteria							
	1		**2**		**3**		**4**	
	Design X	**Design Y**	**Design X**	**Design Y**	**Design X**	**Design Y**	**Design X**	**Design Y**
Designer A	0.7	0.9	0.9	0.9	1	1	0.8	0.7
Designer B	0.8	0.8	0.9	0.9	1	1	0.7	0.9

Table 5. Aggregate Hurwicz payoff value.

	Criterion 1		**Criterion 2**		**Criterion 3**		**Criterion 4**		**Total X**	**Total Y**
	Design X	**Design Y**	**Design X**	**Design Y**	**Design X**	**Design Y**	**Design X**	**Design Y**		
Designer A	18.20	24.70	16.20	16.20	26.00	26.00	13.30	9.80		
Designer A	20.80	23.40	16.20	16.20	26.00	26.00	12.95	12.60		
Average of Design X	19.50		16.20		26.00		13.13		61.70	
Average of Design Y		24.05		16.20		26.00		11.20		77.45

4.5. Cycle Repetition

After the best design has been agreed upon, the CAD program will make a copy of the chosen design and propagate the design to all the involved designers. The chosen design will then be used as a base for further development of the design, which means that the chosen design can next be independently modified by each designer to be added and assembled with other embodiment designs to realize other product functions that have not been addressed. When another significant difference between the embodiment designs arises, one of the designers will then once again initiate the design evaluation process mentioned before. This cycle will then be repeated until all the functions and subfunctions of the product have been paired with one or more product parts generated from the embodiment design process.

For this example, the next embodiment design phase continues with the design for the function 'Prevent Slipping'. This can be verified through the CAD program, where it will show in the Database Module that only the functions of 'Support Bodyweight' and 'Direct Bodyweight' have been paired with the embodiment designs, namely, the 'cane body' and the 'cane handle', and there are no generated designs paired yet with the function 'Prevent Slipping'.

The embodiment design generated for the function 'Prevent Slipping' is a combination of the shape and material at the 'cane tip'. The design aims to create a sufficient coefficient of friction on common walking surfaces, such as is shown in Figure 9. The design evaluation performed for this embodiment design only needs one technical criterion, which is the 'coefficient of friction', and one function, which is 'Prevent Slipping'. This can be achieved when the designers have judged that the 'cane tip' can independently function from other parts of the cane, as described in the first situation in the preceding section. Therefore, the design comparison is performed using one technical criterion with a weight of 100, as shown in Table 6.

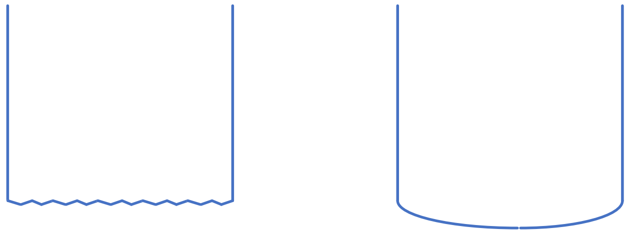

Figure 9. Cane tip design for Design X (**Left**) and Design Y (**Right**).

Table 6. Hurwicz payoff value for the next phase of the design.

	Performance Value		**Coefficient of Optimism**		**Hurwicz Payoff Value**
	Min	**Max**	**Designer A**	**Designer B**	
Design X	0.7	0.75	0.95	0.9	92.5
Design Y	0.72	0.75	0.8	0.8	88

At this stage, all the functions and subfunctions have been associated with an embodiment design that is designed to realize the functions. They are as follows: the 'cane body' is paired with the function 'Support Bodyweight', the 'cane handle' is paired with the function 'Direct Bodyweight', and the 'cane tip' is paired with the function 'Prevent Slipping'. Meanwhile, the function 'Able to Move Easily' is associated with all the designed parts because it is realized from the combination of the technical attributes from all the different parts. Therefore, the conceptual–embodiment design phase is finished, and the design activity can proceed to the detail design phase.

5. Discussion and Future Work

The CAD framework proposed in this paper aims to facilitate collaborative design during the conceptual–embodiment design phase. The focus of the framework is to provide an integrated space for the designers that can be used to track and compare ideas regarding the product functions and their physical embodiments. As such, there are many aspects of the design workflow that are out of the scope of the proposed framework and it is left to the designers to communicate and come to a consensus regarding those issues, such as translating the functions into the corresponding technical criteria or choosing which functions will be the starting point of the design activity. These tasks are highly unstructured and difficult to formalize into systematic procedures; as such, their formalization has potential for future research and improvement in the proposed CAD framework.

The selection of functions and the design of their embodiment through a physical form is one of the core parts of the design activity, such as shown in the 'zigzagging' activity of the axiomatic design methodology [72]. In axiomatic design, designers are encouraged to move between the Functional Domain to the Physical Domain in a hierarchical manner such that every function can be detailed into its basic function. Our proposed CAD framework supports the 'zigzagging' movement described by the axiomatic design theory by encouraging designers to switch between the problem space and the solution space as the evolution of the design continues organically, that is, when an embodiment design necessitates a modification to the previous functional decomposition, and vice versa when a new version of the functional decomposition necessitates the identification of a corresponding embodiment design. As such, we feel that framing the 'zigzagging' movement as being mainly performed during the conceptual–embodiment design phase instead of the detail design phase or the Functional Design phase is more in line with the collaborative Coevolution Design Theory, which focuses more on the iterative nature of the design process.

During the collaborative early design phase, the zigzagging movement between multiple designers will 'lock' the designers into an agreement when discussing the top-level functions, as the functions on the lower level of the hierarchy are very much dependent on the functions above them, and the way to move down into the lower hierarchy is by first agreeing on the conceptual–embodiment design of the upper-level functions. On the contrary, we envisioned that a collaborative early design phase is more useful when the designers are able to freely express their ideas regarding solutions to the function. As such, defining the functions up until the lowest level and then finding the solutions from the 'bottom up' will give designers more chance to exchange their ideas. Naturally, this necessitates a mechanism to help designers choose the best design alternative; hence, we also proposed the design evaluation method detailed in this paper. According to the Coevolution Design Theory, the zigzagging movement will still happen during the design process when there is evolution of the problem space and the solution space, although we suspect that in complex cases, there could be more iteration during the design cycle with our proposed framework compared to if the axiomatic design theory is adopted in its entirety.

In axiomatic design, the independence axiom is an important design principle that states that each function should be independent of each other. It can be seen that although the independence axiom will greatly simplify the design activity, it does not necessarily need to be fulfilled using our proposed CAD framework. An independent design will produce a 1-to-1 relationship between the number of functions and the number of embodiment designs, but our proposed CAD framework can still be used even for coupled or redundant designs, as shown by the example in the previous section. Although we feel that our proposed CAD framework is able to complement the axiomatic design theory, in the future, further deeper comparisons of our proposed collaborative workflow with axiomatic design theory and other design methodologies can also be performed to improve our proposal.

During the design activity, the selection of the first function that will be developed into an embodiment design can heavily influence the whole design activity. For now, it is assumed that the designers will be able to pinpoint the core functions that should be developed through their own knowledge and by communicating with other designers involved in the design activity. For modular products, the selection of the first function can be simplified by first determining which existing modules can be utilized to realize the functional requirements and which requirements must be realized by new modules. The database function in our CAD framework will be able to assist in this process as it will make it easier to find designs that can satisfy a particular requirement.

This research has also proposed a novel framework for comparing early designs by utilizing the Hurwicz criterion. The proposed design comparison method is also developed by combining this with the House of Quality method. The joint determination of the technical criteria and its importance for the stated function is currently out of the scope of this paper, but it is assumed, once again, that the designers involved in the design activity will be able to come to a consensus regarding these matters.

The proposed CAD framework is still only in the early stage of development and will gradually be expanded into an integrated CAD system in future research. As such, the proposed CAD framework contains many limitations, largely owing to the nature of the collaborative conceptual–embodiment design stage, which contains complex and unstructured tasks. Communication between designers is essential in every step of the design process, but the proposed CAD system does not contain a feature to allow communication, and it is assumed that designers will be able to use other means to help them communicate during the process. From the workflow that has been suggested, there are many steps that can be improved by introducing further guidelines or algorithms that can help in increasing the efficiency of the design process. For example, the functional decomposition module can be developed further to include means to guide designers to come to an agreed-upon functional decomposition of the product. As it stands now, the design process can be delayed if the designers cannot come to an agreement for the functional decomposition or they encounter difficulties in communicating their ideas to one another.

Similarly, when the embodiment design process starts, the designers should agree upon which functions they want to choose to develop first, and it is assumed this can be achieved without help from the system. Guidelines for this step can help to increase the efficiency of the process by allowing the designers to come to an agreement faster. Another limitation is in the selection of the best embodiment design, where the designers are once again assumed to be able to list the relevant technical criteria that pertain to the fulfillment of the particular product function, give the weights for each technical criterion, and come to an agreement regarding them. In the future, the system could be developed further by giving suggestions of technical criteria that have been historically relevant to its function. Also, an algorithm for aggregating the weight of each criterion from the different weights given by the designers can further help in streamlining the process and reducing the need for lengthy communication between the involved designers.

As mentioned before, the case study that we have shown is very simple and meant to illustrate the workflow of our proposed framework. A complex design case which entails a larger number of functions will naturally increase the number of parts needed to fulfill the functions, as well as the technical criteria needed to compare and choose the best alternative designs. Our collaborative CAD framework is expected to help this situation by partitioning the design process into the design and selection of small groups of parts, as shown by the workflow. On the other hand, there is a higher chance that the design time could be lengthened greatly due to the number of communications and deliberations needed among the involved designers regarding such matters as the creation of the function decomposition, determination of technical criteria weight, etc. As a result, the guidelines and algorithms mentioned to help designers in these aspects will become more important to be added to the framework through future research.

In the future, our work will continue by developing the framework into a fully realized CAD program with all the capabilities stated in this paper. Research is ongoing to create an integrated CAD system containing the functionalities stated above. Although, currently, the technologies for the stated modules of the program are already available, i.e., a chart- and diagram-making software to create functional decompositions, a 3D modeler to create embodiment design, etc., the challenge lies in combining them into an integrated design environment that can enable designers to collaborate in a seamless manner. The collaborative design framework itself will be further tested in the next phase of our research by conducting design cases using the framework in an experimental setting. It is hoped that this experiment will be able to reveal further limitations of the framework so that the findings can be used to further improve the workflow and efficiency of the framework. Moreover, although our simple case study is capable of illustrating the basic workflow of our framework, the evolution of the functional diagram and the design have not been shown in this paper. This will also be handled in the experimental setting, as we hope that real-life designers will be able to show the evolution process when the design case is increased in its complexity.

In conclusion, this paper presented a preliminary CAD-based framework for collaborative conceptual–embodiment design that can be developed further into an integrated CAD system to increase the efficiency of the collaborative early design phase. Although there are still limitations of the proposed framework, nevertheless, it has been shown that the framework combines the conceptual design stage and the embodiment design stage in line with the Coevolution Cognitive Design theory, enabling designers to exchange design ideas and guiding the design process by pairing the functions of the product with the embodiment design that realizes the function. As such, it is hoped that the proposed CAD framework is helpful for designers engaging in the conceptual–embodiment design process, especially after the framework has been developed further into a functioning CAD system with all the features introduced in this paper.

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