DRAFT

The Situated Function-Behavior-Structure Co-Design Model

John S Gero and Julie Milovanovic

Abstract:

This article presents the situated Function-Behavior-Structure (sFBS) model of co-design, developed within the FBS ontology. In co-design, designers interact with their co-designers and with their own cognitive experiences. In this model, we describe a representation of the overall co-design activity, while preserving a fine-grained representation of each designer's interactions with their co-designers and with their internal cognitive processes. The relevance and potential of our model are illustrated through multiple examples.

Key words: collaborative design, design models, design cognition, design theory

Up until the early 1990s, design research primarily focused on analyzing and modelling individual design processes. Collaboration in design became essential with the growing complexity of design artefacts, a higher need for innovation and an increasing demand for time efficiency. Ostergaard & Summers' (2009) taxonomy of collaborative design highlights its six main attributes: the team composition, communication, the distribution of people and location (co-located or dispersed), the nature of the design problem, design information (generated, used and refined by the team) and the design approach (tools, protocols). The complexity of design collaboration is found in the many issues appearing at the interface of those attributes. In collaborative design, teams, which involve multiple actors with different backgrounds and levels of expertise, have to work simultaneously on a unique design artefact. Multi-site project developments imply both collocated and distant collaboration, as well as synchronous and asynchronous co-design, which raise challenges in terms of media to support co-design communication (Kvan, 2000).

In co-design, team members share the same objective, as their goal is to co-develop and co-construct design solutions. Teamwork in design can also be described as distributed design (Darses, 2009). Within it, members work individually on their sub-tasks and co-operate on their project, but might not adopt common design processes and strategies. In the present study, we will only focus on co-design situations. Compared to individual design, a co-design activity is not only focused on the design content itself, but also on the organization of the group process in order to structure and organize the activity (Stempfle & Badke-Schaub, 2002). Synchronization between team members on both design thinking (cognitive synchronization) and design task coordination (synchronization of actions) is a co-designing prerequisite (Darses & Falzon, 1994).

Protocol analysis (Ericsson & Simon, 1984), primarily used to study individual cognitive processes, has been widely adopted to analyze team thinking processes in co-design situations (Darses, Détienne, Falzon, & Visser, 2001; Dorta, Lesage, Pérez, & Bastien, 2011; Stempfle & Badke-Schaub, 2002; Valkenburg & Dorst, 1998; Wiltschnig, Christensen, & Ball, 2013). In those studies, the team's design activity unfolds within a framework that explores implicit signs of collaboration through actions such as negotiating, clarifying, and assisting goal planning; or design processes like generating a proposal, analyzing a solution, or evaluating. Other empirical studies focused on specific concepts such as the comparison between individual design and co-design (Goldschmidt, 1995), the stimulation processes in design thinking (Sauder & Jin, 2016), the impacts of alternative media environments (Dorta, Kalay, Lesage, & Pérez, 2011; Eris, Martelaro, & Badke-Schaub, 2014; Tang, Lee, & Gero, 2011), the development of team expertise (Gero & Kannengiesser, 2004a), or the relationship between collaborative design and social cues (Cross & Clayburn Cross, 1995).

The frameworks used to analyze co-design in the studies mentioned above are mostly categorical description of design actions undertaken by the team (for example generating, analyzing, reflecting) or implicit markers of design collaboration (such as negotiating, clarifying). Results from empirical studies using protocol analysis provide interesting insights to better understand co-design, but lack a formal representation of cognitive design processes and team interactions occurring during co-design situations. Formal descriptive models of co-design have the potential to give a dynamic representation of the co-design activity, while representing qualitative and quantitative information about co-design behaviors, extracted from protocol analysis. From their literature review on design group creativity, Sauder & Jin (2016) pointed out different types of models and their limits. Process models describe the overall design processes where the team is considered as a single entity and the activity is looked upon in an integrated manner (Chiu, 2002; Sonnenburg, 2004; Stempfle & Badke-Schaub, 2002). Interaction models (called aggregate models by Sauder & Jin, 2016) focus on members' individual participation to the activity, and their interactions. Here, the team's creativity is considered as the sum of each individual's creativity (Pirola-Merlo & Mann, 2004). Process model representations lose the quality of the interaction between members since the team is considered as a unique entity. Therefore, the number of team members and their input into the activity, which affects the team thinking process, are not taken into account. On the other hand, interaction models highlight individual contributions to the team's creative activity but, as underlined by Sauder & Jin (2016), individuals are considered as a black-box, and their internal thinking processes are disregarded.

Despite the effort invested in studying co-design, a knowledge gap appears in the development of a formal descriptive model of co-design that will:

- conserve a fine-grained representation of team members as units while describing the collaborative design activity as a whole;
- acknowledge the situatedness of design activity, which implies that the model considers both internal cognitive thinking processes linked with the designers' experiences and external visible processes altered by the designers' interactions with the design situation.

The aim of this article is to propose such a model, describing individual and co-constructed cognitive processes occurring while co-designing. This model is developed based on the situated Function-Behavior-Structure (sFBS) framework (Gero, 1990; Gero & Kannengiesser, 2004b), adapted to a multiple designers setting. The FBS ontology offers a description of design elements present in the design space as well as their transformation through a discrete set of design processes (Gero, 1990). The situated FBS framework accounts for internal thinking processes that designers undertake while designing (Gero & Kannengiesser, 2004b).

The strength of our model is twofold: it builds on a widely used ontology (examples are found in Hamraz, Caldwell, Ridgman, & Clarkson, 2015; Masclet & Boujut, 2010; Pauwels, Strobbe, & De Meyer, 2015), and it provides a framework to analyze co-design protocols and formally display commensurable quantitative and qualitative results inferred from the protocol analysis. The significance of the model lies in its adaptability to design situations, since this unique model can be used to study diverse settings, ranging from team design in practice, tutor/student collaboration during pedagogic design critiques, to co-creative human-computer design. Moreover, the model is scalable and can represent collaborations from two-designer collaboration to multiple designer collaborations.

In the first section, we present co-design based on previous work, and depict the frameworks and models used to analyze the co-design activity. The second section describes the FBS ontology in which our model is developed. An explanation of the construction of the situated FBS co-design model in the case of a two-designer situation is the focus of the third section. To illustrate the potential of our model as a tool to represent and provide commensurable information on co-design cognitive behaviors, several examples are given, representing: quantitative semantic distribution of co-design processes, dominant co-design processes based on a first order Markov model, design problem/solution space transitions and temporal dynamic evolution of co-design processes over a design session. The last part of the paper discusses the significance of the sFBS co-design model in terms of its adaptability and scalability.

1 Co-designing: frameworks and models

In co-design situations, the principle of mutual responsibility of collaborative conversation applies, implying that both speakers and listeners assent that the others have a sufficient understanding of the last utterance formulated in order to proceed (Clark & Wilkes-Gibbs, 1986). Design team members have to understand what the others are referring to in order to co-construct a design proposition. Team communication is essential to allow cognitive synchronization between team members. A shared knowledge of the design situation, that is to say the design problem, its requirement and the state of the design, and a shared awareness of contextual design procedures and technical information are key elements for the team's cognitive synchronization. The goal is to construct a common design reference, or common ground (Clark & Brennan, 1991), in order to integrate each team member's point of view and thinking processes to reach a collective decision (Darses, 2009).

1.1 Frameworks to study co-design

Designers working in teams have to verbally formulate their design thinking in order to communicate with their teammates. According to Goldschmidt (1995), a single designer think aloud protocol is equivalent to the conversation transcript of designers talking while co-designing. This allows a straightforward application of individual design cognition analysis to co-design situations. The frameworks used to examine empirical studies of single designer think-aloud protocols were mapped onto co-design conversation protocols such as Schön's (1983) reflective practice (Valkenburg & Dorst, 1998). Reflection-in-action activities, like naming, reflecting and moving, as well as framing were analyzed at a team level to compare team design behavior and highlight different team strategies. Wiltschnig et al. (2013) considered the problem/solution co-evolution paradigm (Dorst & Cross, 2001; Maher & Poon, 1996) in their analysis of a team in engineering design. In their case study, it was found that two thirds of problem/solution co-evolution episodes occurred collaboratively. Using the linkography methodology Goldschmidt (1990, 1995, 2014) highlighted the similarity between the overall individual design and team design behavior patterns. In individual design, the designer showed a larger range of design behavior patterns, whereas in the team, members assumed specific roles, and mostly relied on their own expertise.

According to Darses et al. (2001), at the task level, single think aloud protocols and multiple design team conversations differ due to the team members' interactions or their implicit underlying reasoning. Therefore, frameworks used for individual design should be adapted to a co-design situation. To include design-related activities and team-related activities, the COMET method (Darses et al., 2001) proposes two levels of coding design conversations. The basic-level code is applied to single units and represents design actions like generating, informing and evaluating. The second-level code represents the aggregations of single units that are co-operation moves related to the task level. A similar coding framework, is proposed by Stempfle & Badke-Schaub (2002) and distinguishes content-based activities (goal clarification, solution generation, analysis, evaluation, decision and control) and team-process-oriented activities (planning, analysis, evaluation, decision and control). Those activities are dependent on four cognitive processes: exploration, generation (extracted from the Geneplore model of creative thinking, see Finke, Ward, & Smith, 1992), comparison and selection (based on the evolutionary paradigm of natural selection). In their study, the teams spent around one third of their time on team process activities and two thirds on interacting with the design situation.

We would argue that on the design activity level, single and multiple-designer situations are indeed similar because utterances expressing design knowledge are similar in both cases. Therefore, a co-design coding framework can be built upon existing design frameworks developed a priori to represent single designers' activities. We acknowledge that due to the social dimension of collaborative design and the importance of team communication, the team's conversation contain organizational moves that would not appear in a single designer protocol.

All empirical case studies referenced above analyze and measure team design activities as a whole, not taking into account the contribution of each actors. In their framework to study signs of collaborative ideation in design conversations, Dorta et al., (2011) take into consideration actors' individual participation, as well as team members collaboration. Their coding scheme is divided into six elements: naming, constraining, proposing, negotiating, decision-making and moving. Patterns of design collaboration such as Collaborative Conversation, Collaborative Ideation loops and Collaborative Moving are defined as sequences of different design conversation elements uttered by at least two designers.

1.2 Models of co-design

Modelling design activity provides formal representations of the underlying processes that drive that activity. Co-design models tend to focus on either illustrating the team's activity (process models) or team members' participation to the activity (interaction models) (Sauder & Jin (2016). Process models of co-design are described in steps similar to single designer models of design. They include processes such as 'clarifying design goals', 'generating solutions', 'evaluation' and 'decision making'. Interaction models, on the other hand, focus on the designers' contributions to the design space, their interaction with one another and with the design situation.

1.2.1 Team process models

Chiu (2002) proposes a four-stage loop model of collaborative design resulting from several case studies of architectural practices and design studios. The initial state of the design situation is altered through collaborative reflection, consultation, negotiation and decision-making. A more detailed stage model of creativity in collaboration is proposed by Sonnenburg (2004), which integrates co-occurrences, interrelations and feedback loops within each of the eight steps. From the problem to the solution proposal, the team goes through phases such as preparation, illumination and verification. These models can be synthesized by mapping Gibson's (2001) model of collective cognition in team work to a collaborative design activity (Figure 1).

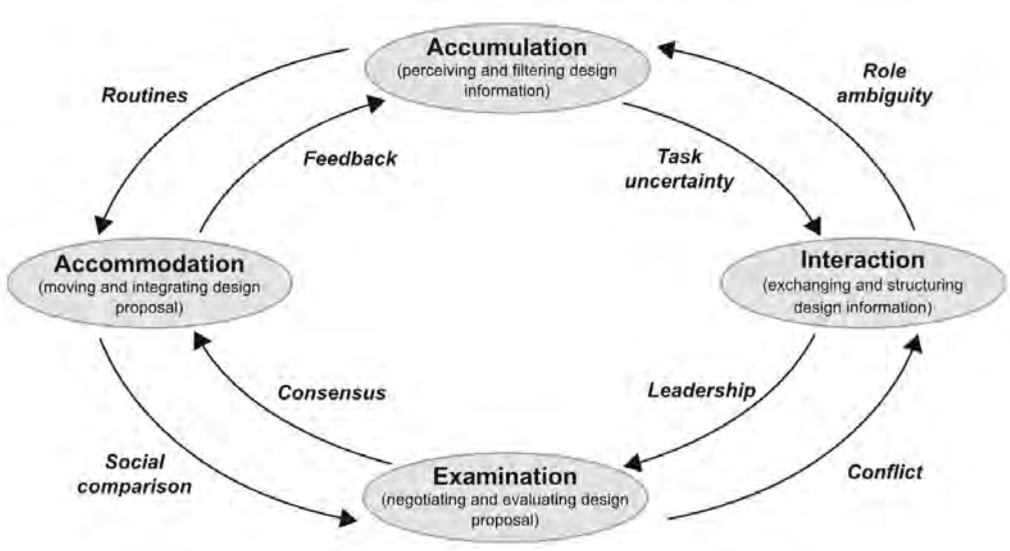


Figure 1. Process model of co-design, authors' interpretation, based on Gibson's (2001) model of collective cognition

This model includes four steps: accumulation, i.e. perceiving and filtering design information; interaction, which refers to retrieving, exchanging and structuring design information; examination that involves negotiating, interpreting and evaluating design proposals; and accommodation, centered around decision-making, acting (or moving) and integrating a design proposal. As shown in Figure 1, several catalysts, related to social factors, depict bi-directional movements from phase to phase, emphasizing the non-linear organization of co-design activity. From the accumulation of design information stage, the design activity can move to the accommodation phase if design routines are enough to address the design task. On the other hand, task uncertainty and design problem complexity might call for further examination of the design situation if design strategies to undertake the task are unknown. In that case, the group will move from the accumulation phase to the interaction phase. During the organization of design information and the clarification of design goals, the emergence of leadership in the team will push the activity towards examination, whereas role ambiguity will lead to a new phase of accumulation of design information. While negotiating and evaluating possible design solutions, the team will move to the accommodation phase if they reach a consensus on design strategies and proposals. The consensus echoes the notion of grounding and sharedness of team mental models (Klimoski & Mohammed, 1994; Mohammed, Ferzandi, & Hamilton, 2010). Conflicts between members on how to proceed with the design task will require a new moment of interaction to restructure design knowledge. Accommodation is likely to be followed by a phase of accumulation of new knowledge if the former design move receives positive feedback from the group. On the other hand, a comparison of the design proposal with others, outside of the group, might reveal negative critiques related to the newly implemented design move, and therefore encourages a re-examination of the design situation.

1.2.2 Team interaction models

Sauder & Jin (2016) propose a bridge between studies on individual creative cognition and group creativity. Their study focuses on team interactions with the design situation and interactions between team members. They highlighted the drawback of team interaction models that considers individuals' creativity as a black-box, and they thus proposed a model that distinguishes between designers internal and external thought stimulation, Figure 2. The model is based on the assertion that each designer's externalized design entity is the major source of collaborative stimuli. A categorization of designers collaborative actions on the design entity is given, based on four possible interactions: prompting occurs when a design entity proposed by designer A reminds designer B of a memory that he/she will externalize in the design space; seeding appears if designer B builds on designer A's design entity; correcting takes place when designer A refines his/her design entity because designer B challenges it, and clarifying accounts for an extrapolation of designer A's own design entity if he/she notices that designer B does not understand it fully.

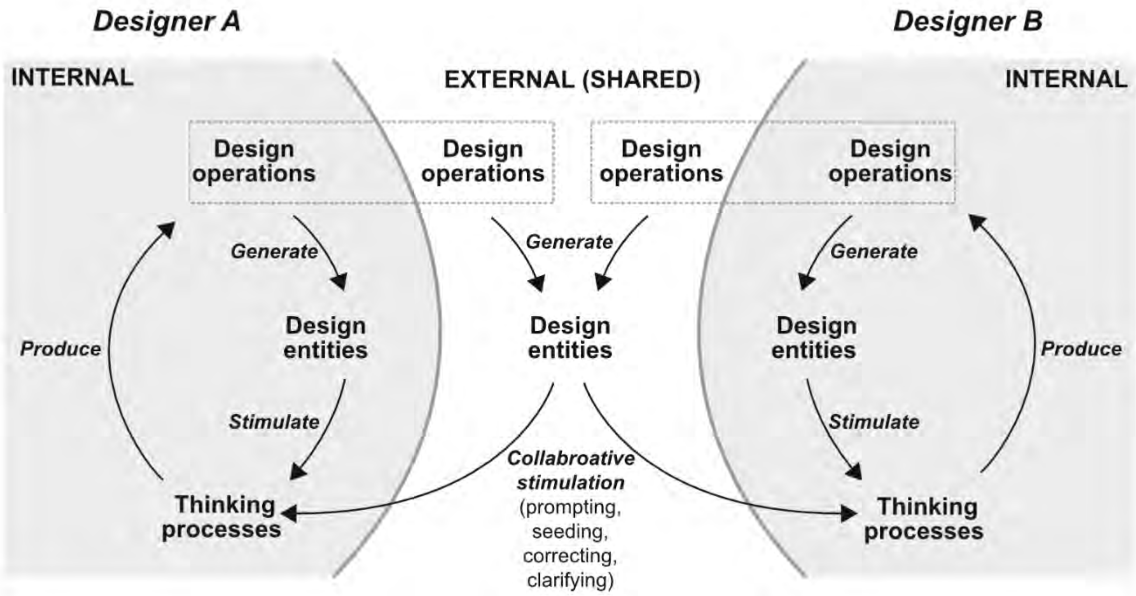


Figure 2. Collaborative thought stimulation, authors' interpretation based on (Sauder & Jin, 2016)

1.2.3 Limits

Team process models have the potential to display how design-related actions and teams' social behavior intertwined. The major pitfall of such models is that individual qualities and participations are lost in a general model where the team is considered as a single entity. The interactions models preserve the individual scale representation but lack clarity in representing individual internal thinking processes. Sauder & Jin's (2016) model proposal acknowledges both internal and external cognitive processes in co-design, offering a more detailed representation of co-design cognitive processes. Their model shows a feedback loop, or ping-pong process, between designers and the shared external design entities. Designers alter the external space through design entities that has a double effect in affecting their own stimulation processes and the other's stimulation processes. The reflective quality of the design activity, considered as a dynamic conversation with the external materials of the design space (Schön, 1992) is accounted in their definition. Nonetheless, only one part of the situatedness of design is represented. Indeed, through past experiences, designers acquire design prototypes (Gero, 1990), also called repertoires (Schön, 1983) or schemata (Lawson, 2004) that situate the design activity at a personal and internal level. A representation of the effect of design prototypes on co-design activity can only be observed while considering designers' internal cognitive processes.

We intend to obviate the limits of current co-design models and frameworks by considering the situatedness of the co-design activity, individual and co-constructed design processes and designers' interaction with each other through the funnel of external design representations.

2 The FBS and situated FBS ontologies

2.1 The FBS framework

The FBS ontology gives a description of design knowledge and design processes during a design activity (Gero, 1990). This ontology represents six design issues and eight design processes at the ontological level, Figure 3. Requirement (R) include the design brief, clients or regulations requirements. Function (F) is the design object teleology i.e. what the design object is for. Behaviors represent how the design object performs: it can be an expected behavior (Be) or a behavior derived from the structure of the design object (Bs). Structure (S) is the description of elements or groups of elements of the design object and their relationships. Description (D) are externalizations representing the design object. Requirement are on function, behavior and/or structure and do not require any additional ontological concepts beyond F, B and S. Similarly, descriptions are of function, behavior and/or structure and do not require any additional ontological concepts beyond F, B and S. Hence, only FBS are the ontological concepts on which the design issues are founded.

Eight transformations from one issue to another describe design processes as shown in Figure 3. Formulation expresses a transformation of a requirement (R) into a function (F) or a function (F) into an expected behavior (Be). Synthesis is the transformation of an expected behavior (Be) into a structure (S). Analysis is the transformation of a structure into a behavior that is derived from it (Bs). Evaluation is the comparison between an expected behavior (Be) and a behavior derived from structure (Bs), and inversely. Documentation is the transformation of structure (S) or less often function or behavior into a description (D), which can be accounted for a production of an external representation. Reformulation processes always start from a structure (S) that will redefine some variables in the design space. Reformulation 1 is a redefinition of a structure variable (S). Reformulation 2 is the redefinition of expected behavior variables (Be). Reformulation 3 is the revision of function variables (F).

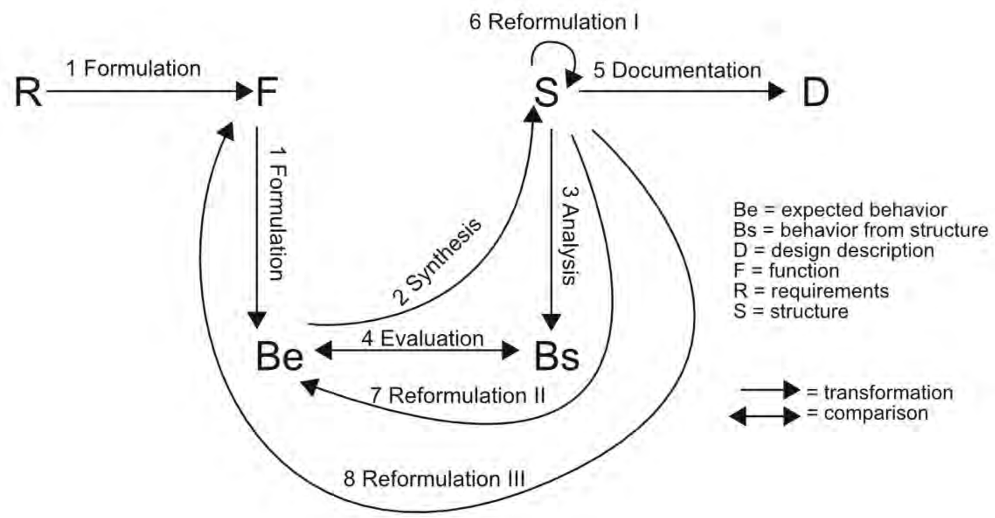


Figure 3. FBS framework showing design issues and design processes (based on Gero, 1990)

2.2 The situated FBS framework

The notion of situatedness in design takes into account the past experiences and current information from the design environment (social) and the designer (personal). For that reason, each design situation is unique and each designer will react differently to it. The situated FBS framework proposes a cognitively articulated version of the FBS ontology by combining the FBS design processes with four cognitive processes: interpretation, constructive memory, focus and action (Gero & Kannengiesser, 2004b, 2008). Three distinct worlds are identified in the situated FBS: the external world, the interpreted world and the expected world (Figure 4).

The external world holds all external representations of the design situation, verbal and graphic. It comprises all design issues of the FBS ontology (Requirement, Function, Behavior, Structure and Description). The interpreted world is the designer's construction of the design situation based on his/her experience of the external world and his/her current design concepts. The expected world contains the formalization of possible design actions built upon the designer's interpreted world. It sits within the interpreted world and encompasses potential design solutions. In the FBS ontology the design situation is represented by only three issues (Function, Behavior and Structure) in both the interpreted world and the expected world since Requirement and Description, which are external to the designer, can be represented in FBS. Cognitive processes express the navigation from one world to another (Figure 4). Interpretation is how the designer makes sense of and organizes information about the design situation that comes through his/her current sensation of it using their experience. It transforms new input information based on already integrated percepts and concepts. A change in the current concepts in the interpreted world, triggered by input information from the external world is accounted for by constructive memory, and is time-related. Both interpretation and constructive memory are push-pull processes, illustrating interactions between the external and interpreted world for the former and within the interpreted world for the latter. Focusing implies a transformation of variables from the interpreted world that suggests a future design action in the external world. The action process shows an expected change in the design situation based on design expectations, and is the only process visible to the observer. This model offers a mechanistic view of reflection-in-action (Schön, 1983), or see-move-see design sequence (Gero & Kannengiesser, 2008).

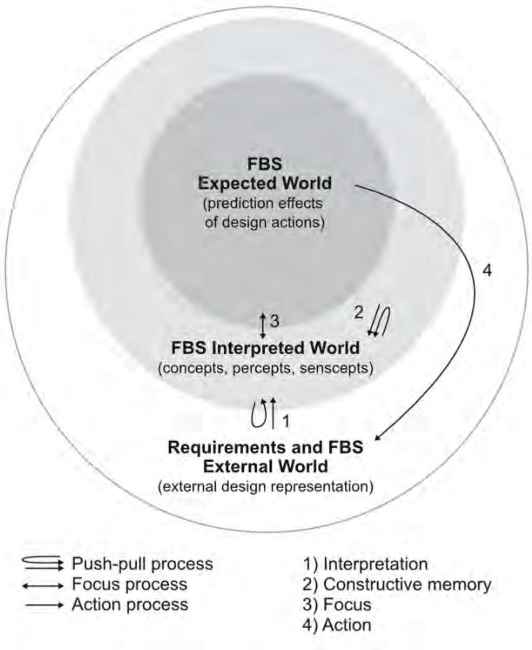
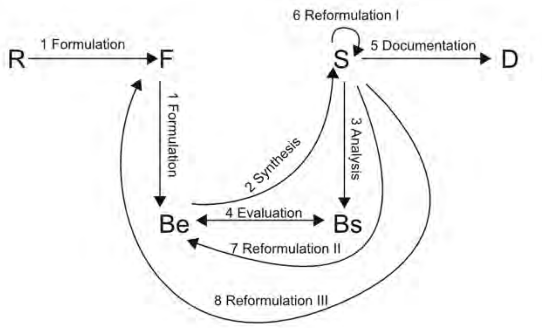
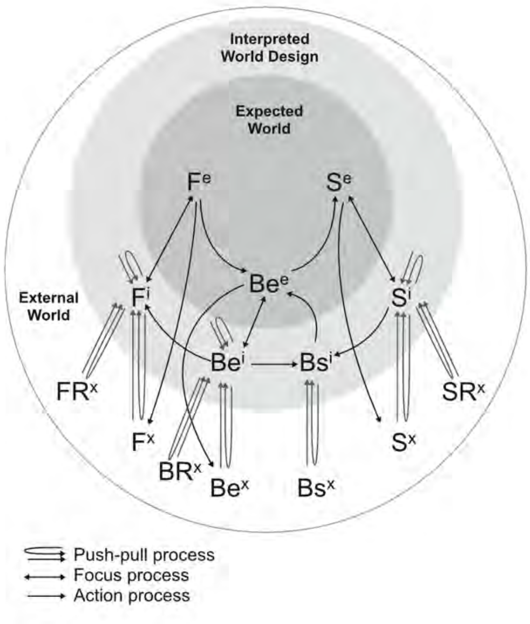


Figure 4. Situated design framework (based on Gero and Kannengiesser 2004b)

The eight processes from the FBS ontology (Figure 5(a)) can be mapped onto the situated design space (Figure 5(b)), where the eight FBS design processes are expanded to twenty situated design processes to account for the cognitive actions involved (Gero & Kannengiesser, 2004b). The framework proposed by Gero and Kannengiesser (2004b) was further articulated to construct the co-design model. In the previous framework, expected behavior (Be) and behavior derived from structure (Bs) were labelled under the same behavior in the interpreted and external world. In this version (Figure 5(b)), seven design issues sit in the external world: function's Requirement (FR^x), behavior's Requirement (BR^x), structure's Requirement (SR^x), Function (F^x), expected Behavior (Be^x), Behavior from structure (Bs^x) and Structure (S^x). Function, expected Behavior, Behavior from structure and Structure have an interpreted instance F^i, Be^i, Bs^i and S^i. An evaluation between the expected and derived interpreted design issues can lead to a focus in the expected world on Function (F^e), expected Behavior (Be^e) or Structure (Se), that will drive an action resulting in a change in the external world of the design's Function (F^x), Behavior (Be^x and Bs^x) and Structure (S^x).s





(a) (b)

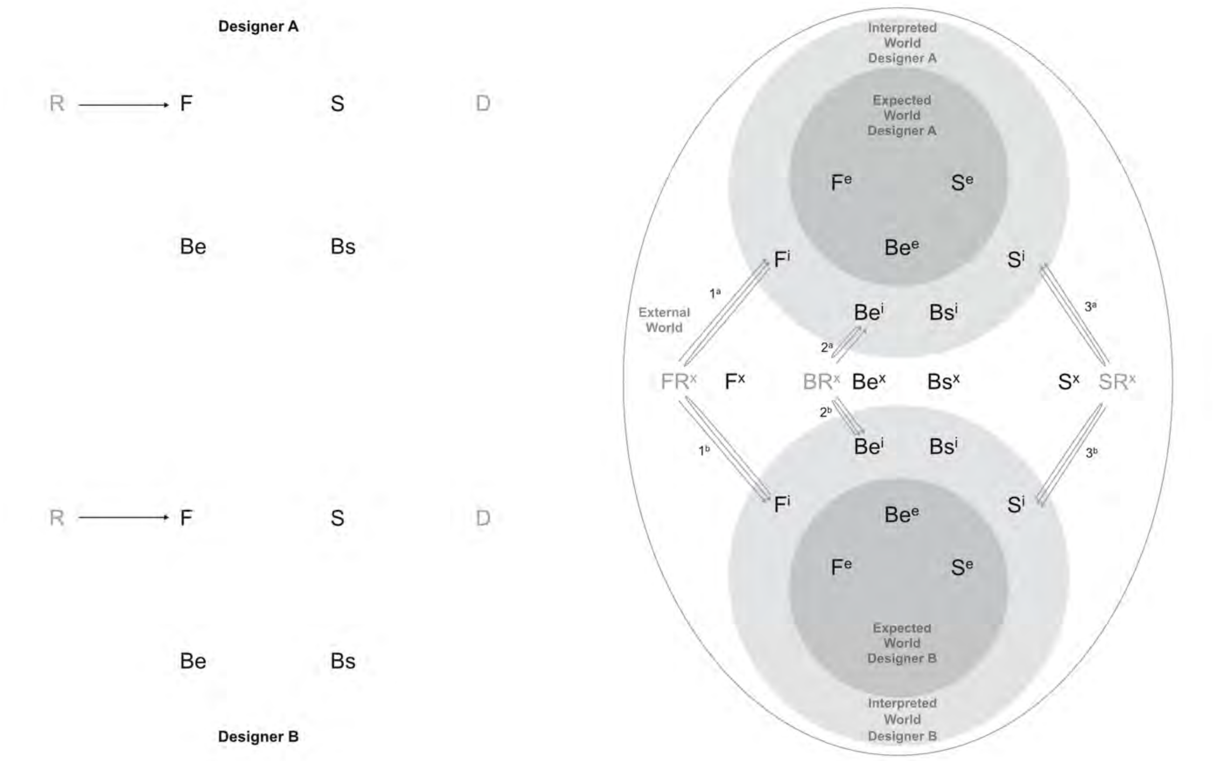
Figure 5. (a) FBS framework, (b) situated FBS framework (based on Gero and Kannengiesser 2004b)

3 Development of the situated FBS co-design model

Co-designing is a collaborative activity sequenced by individually constructed design processes and co-constructed design processes. When designers are co-designing, they communicate through the external world. Each designer formulates design issues that will affect their own and the other designer's cognitive processes. To offer a better understanding of how co-designing functions, we developed a situated FBS co-design model to represent co-designing activity. In the following, we describe a step-by-step development of the situated FBS co-design model. The proposed model is a cognitive extension of the FBS ontology that shows how ontological co-design processes are mapped onto the situated FBS model. As presented in Section 2, a design process in the FBS framework is a transformation of one design issue into another specific design issue. In order to show the development we assume that an FBS co-design process is illustrated by a transformation of a design issue formulated by one designer, followed by a specific design issue, expressed by another designer.

3.1 Formulation: construction of interpreted function, behavior and structure

The Formulation process is defined by two types of processes in the FBS framework: a transformation of a Requirement (R) into a Function (F) (Figure 6(a)) and/or a transformation of a Function into an expected Behavior (Be) (Figure 7(a)). In the situated FBS framework, requirement sit in the external world and are subdivided into three types, requirement regarding function (FR^x), behavior (BR^x) or structure (SR^x). In the case of co-design, the Formulation process expressing a transformation from Requirement (FR^x, BR^x or SR^x) to Function (F^i), expected Behavior (Be^i) or Structure (S^i), remains an individual design process since Requirement is external to both designers (processes 1^a, 1^b, 2^a, 2^b, 3^a, 3^b in Figure 6(b)).

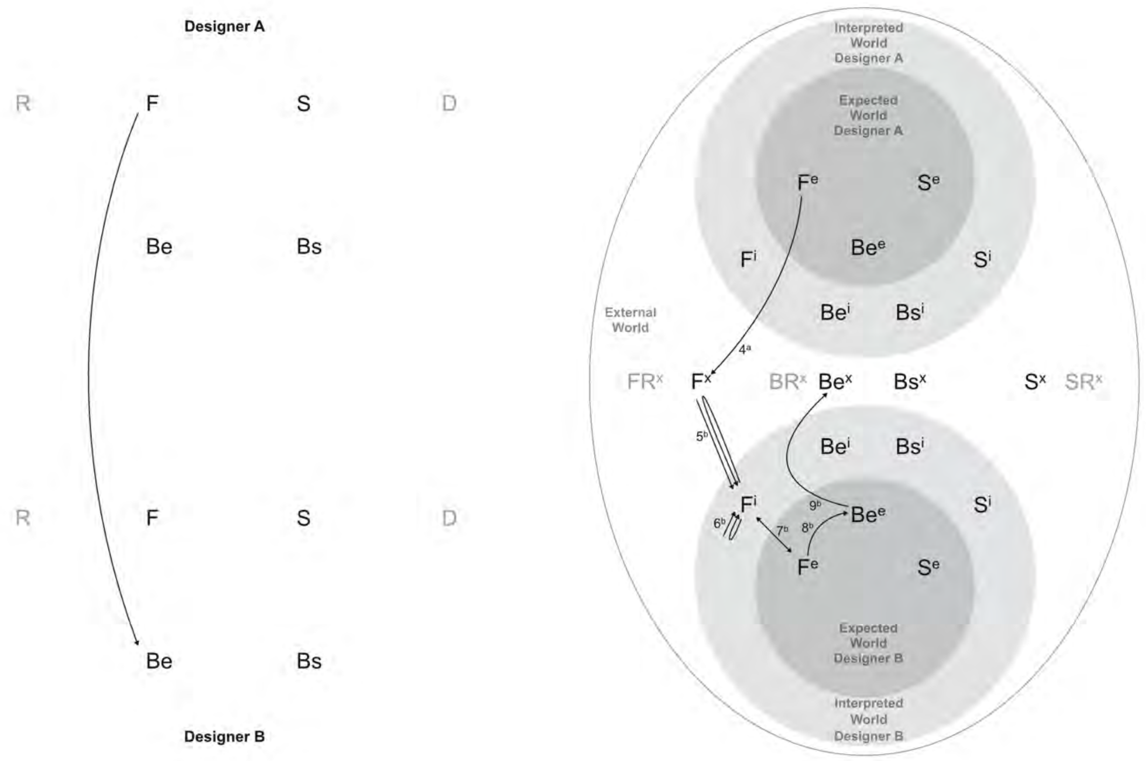


(a) (b)

Figure 6. (a) FBS Formulation, R to F, Be and S, (b) situated FBS Formulation, R to F, Be and S

3.2 Formulation: co-construction of expected behavior from function

The Formulation process describing a transformation of a function (F) into an expected behavior (Be) (Figure 7(a)) can be co-constructed between two designers (Figure 7(b)). Designer A formulates a function in the external world (F^x) based on a function in his/her expected world (F^e) (process 4^a). Designer B interprets that function (F^x) through a push-pull process, generating an interpreted function (F^i) (process 5^b). That interpreted function (F^i) can be enhanced by a constructive memory process (process 6^b). The interpreted function (F^i) produces an expected function (F^e) (process 7^b), which can be transformed into an expected behavior (Be^e) (process 8^b). The expected behavior (Be^e) is then externalized into an external expected behavior (Be^x) (process 9^b).

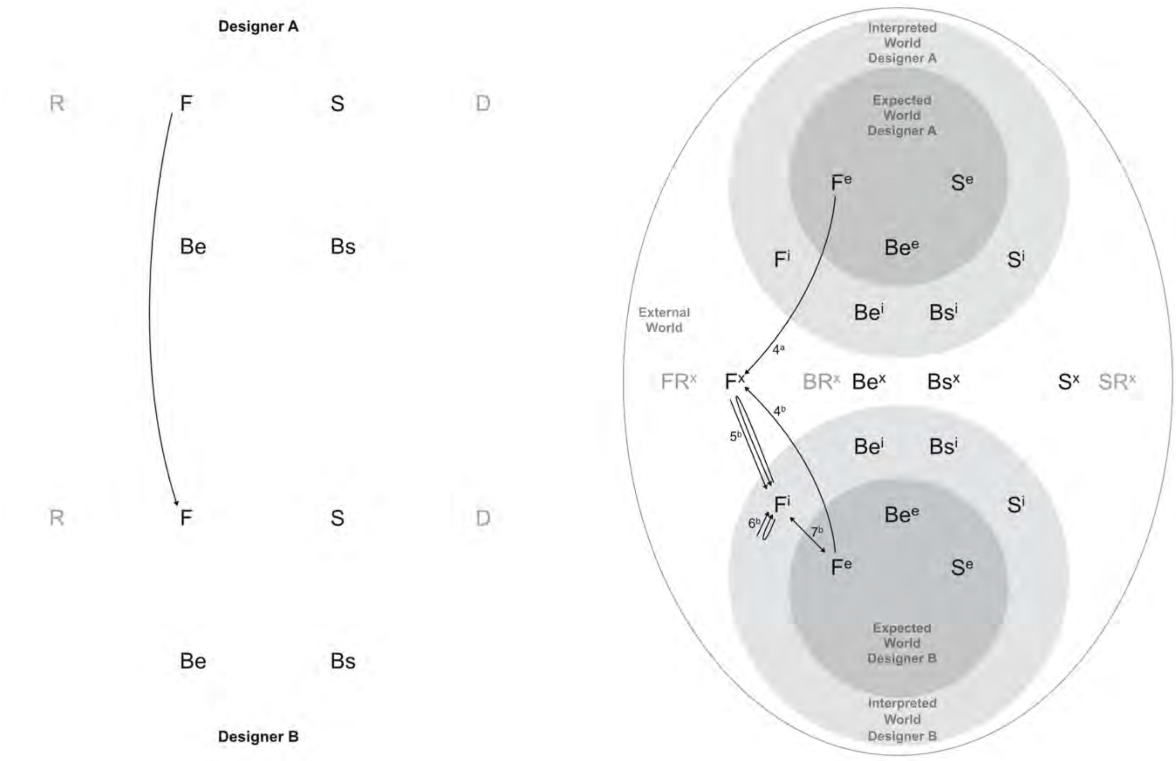


(a) (b)

Figure 7. (a) FBS Formulation by the co-construction of Be from F, (b) situated FBS Formulation by the co-construction of Be from F

3.3 Formulation: co-construction of function from function

In the case of co-constructed Formulation, the transformation from a function (F^e) to another function (F^e) can be considered as a formulation process (Figure 8). Designer A formulates a Function in the external world (F^x) based on an expected function (F^e) in his/her expected world (process 4^a). This function (F^x) is interpreted by designer B into an interpreted function (F^i) (process 5^b) and can be enhanced by a constructive memory process (process 6^b). The interpreted function drives a focus process generating an expected function (F^e) (process 7^b). Designer B externalizes his/her expected function (F^e) into the external world, creating a new function (F^x) (process 4^b).



(a) (b)

Figure 8. (a) FBS Formulation by the co-construction of F from F, (b) situated FBS Formulation by the co-construction of F from F

3.4 Formulation: co-construction of expected behavior from expected behavior

If co-constructed, a transformation of an expected behavior (Be^e) to another expected behavior (Be^e) also represents a formulation (Figure 9). In that case, designer A formulates a behavior in the external world (Be^x) based on an expected behavior (Be^e) in his/her expected world (process 9^a). Designer B interprets that external behavior (Be^x) into an interpreted behavior (Be^i) (process 10^b) that produces an expected behavior (Be^e) (process 11^b). Designer B then communicates the expected behavior (Be^e) into the external world into a Be^x (process 9^b).

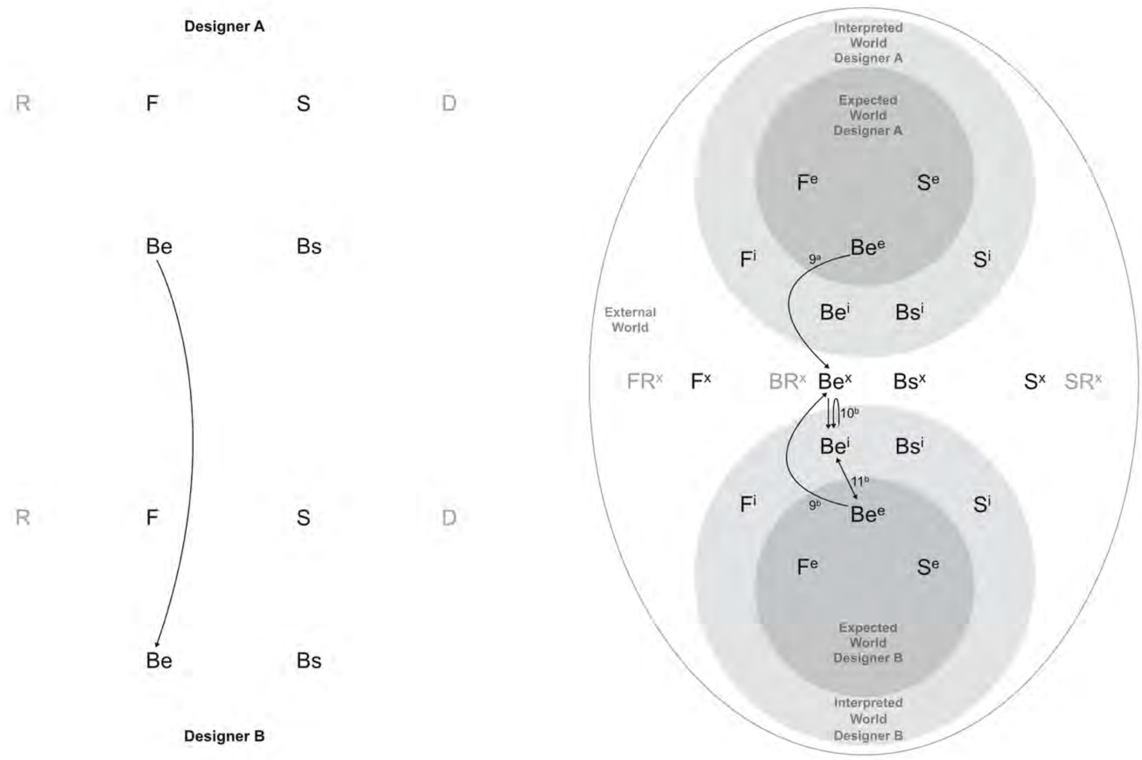
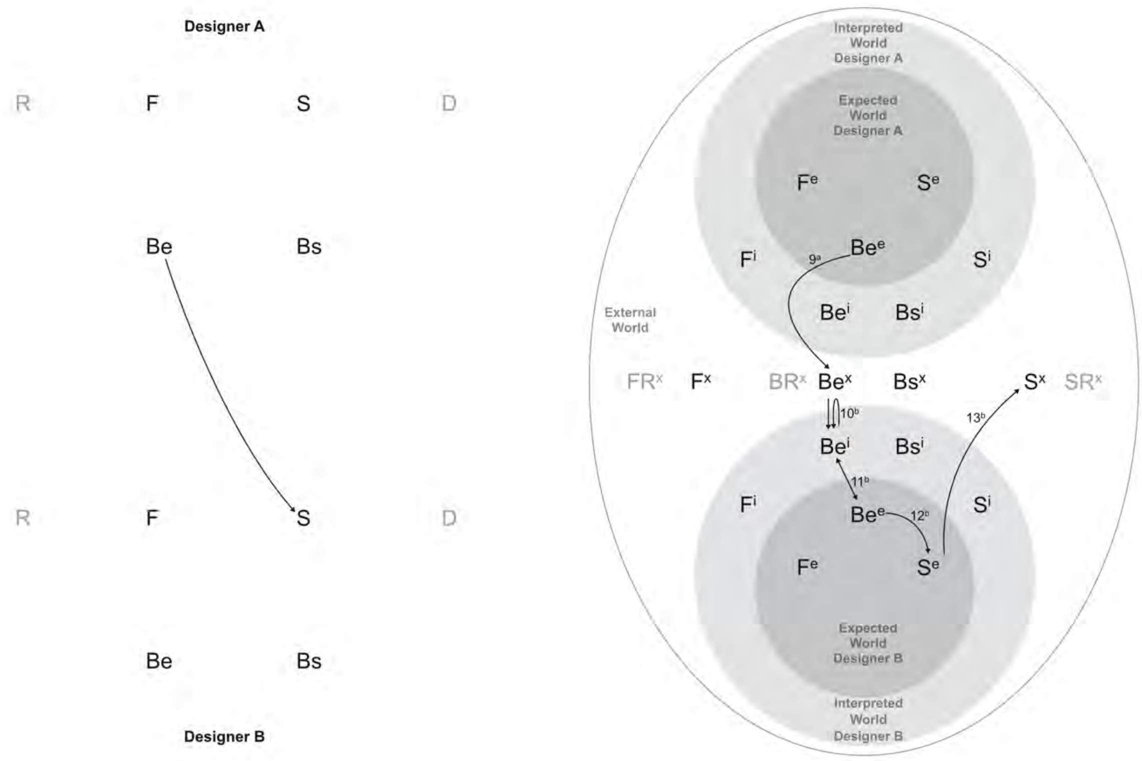


Figure 9. (a) FBS Formulation by the co-construction of Be from Be, (b) situated FBS Formulation by the co-construction of Be from Be

3.5 Synthesis: co-construction of structure from expected behavior

A co-constructed synthesis design process is built on several processes (Figure 10). Designer A formulates a behavior in the external world (Be^x) based on his/her expected behavior (Be^e) (process 9^a). Designer B interprets that behavior in the external world (Be^x) into an interpreted behavior (Be^i) (process 10^b) that produces an expected behavior (Be^e) (process 11^b). This expected behavior (Be^e) is transformed into an expected structure (S^e) (process 12^b), which is then externalized by designer B into a structure (S^x) (process 13^b).

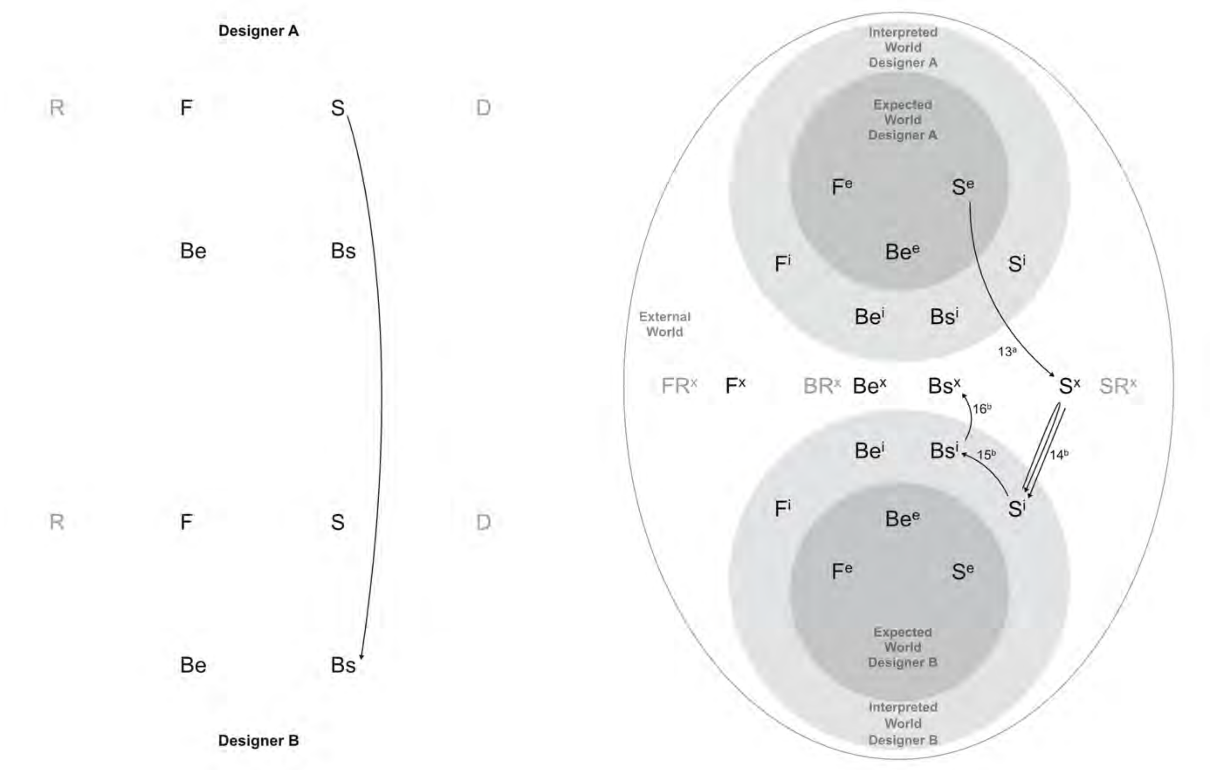


(a) (b)

Figure 10. (a) FBS Synthesis by the co-construction of S from Be, (b) situated FBS Synthesis by the co-construction of S from Be

3.6 Analysis: co-construction of behavior from structure

Co-constructed analysis illustrates a transformation from a structure proposed by a designer into a behavior derived from structure defined by another designer (Figure 11). When designer A formulates a structure in the external world (S^x) based on a structure in his/her expected world (S^e) (process 13^a), designer B can interpret it into a structure (S^i) (process 14^b) that will generate an interpreted behavior derived from structure (Bs^i) (process 15^b). This interpreted behavior (Bs^i) is then externalized by designer B into a behavior from structure (Bs^x) (process 16^b).

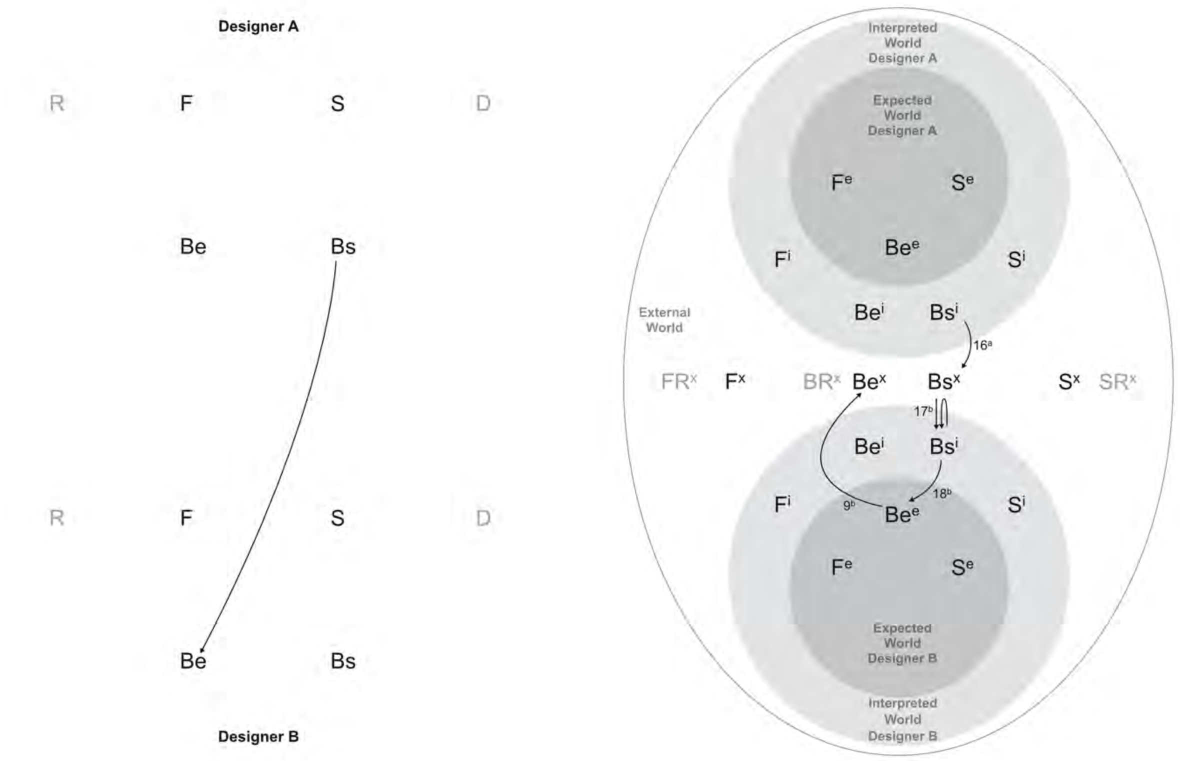


(a) (b)

Figure 11. (a) FBS Analysis by the co-construction of Bs from S, (b) situated FBS Analysis by the co-construction of Bs from S

3.7 Co-construction of evaluation

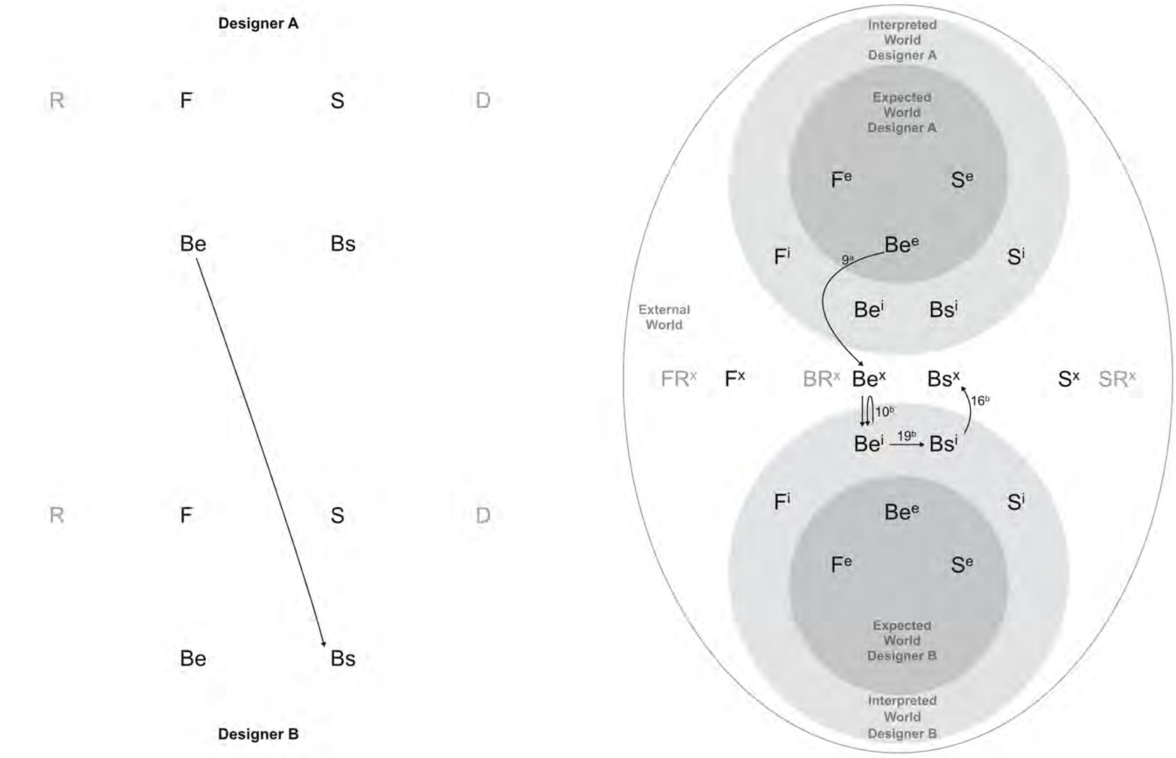
In the FBS framework, an evaluation is a comparison between an expected behavior and a behavior derived from a structure. In co-design, co-constructed evaluation can be a comparison between a behavior derived from structure (Bs) generated by a designer and an expected behavior (Be) from another designer (Figure 12), or inversely (Figure 13). In the first case, designer A expresses a behavior derived from structure in the external world (Bs^x) based on a behavior from structure set in his/her interpreted world (Bs^i) (process 16^a). The behavior derived from structure in the external world (Bs^x) is interpreted by designer B (process 17^b). The interpreted behavior (Bs^i) is then compared to an expected behavior in the expected world (Be^e) (process 18^b). The expected behavior (Be^e) is then externalized by designer B into an expected behavior (Be^x) the external world (process 9^b).



(a) (b)

Figure 12. (a) co-construction of Evaluation, Bs to Be, (b) situated FBS co-construction of Evaluation, Bs to Be

In the second case, designer A expresses an expected behavior in the external world (Be^x) based on an expected behavior set in his/her expected world (Be^e) (process 9^a). Designer B interprets the external behavior (Be^x) into an interpreted expected behavior (Be^i) (process 10^b) that is compared with an interpreted behavior derived from structure (Bs^i) (process 19^b). The interpreted behavior derived from structure (Bs^i) is then communicated into the external world into a Bs^x (process 16^b).

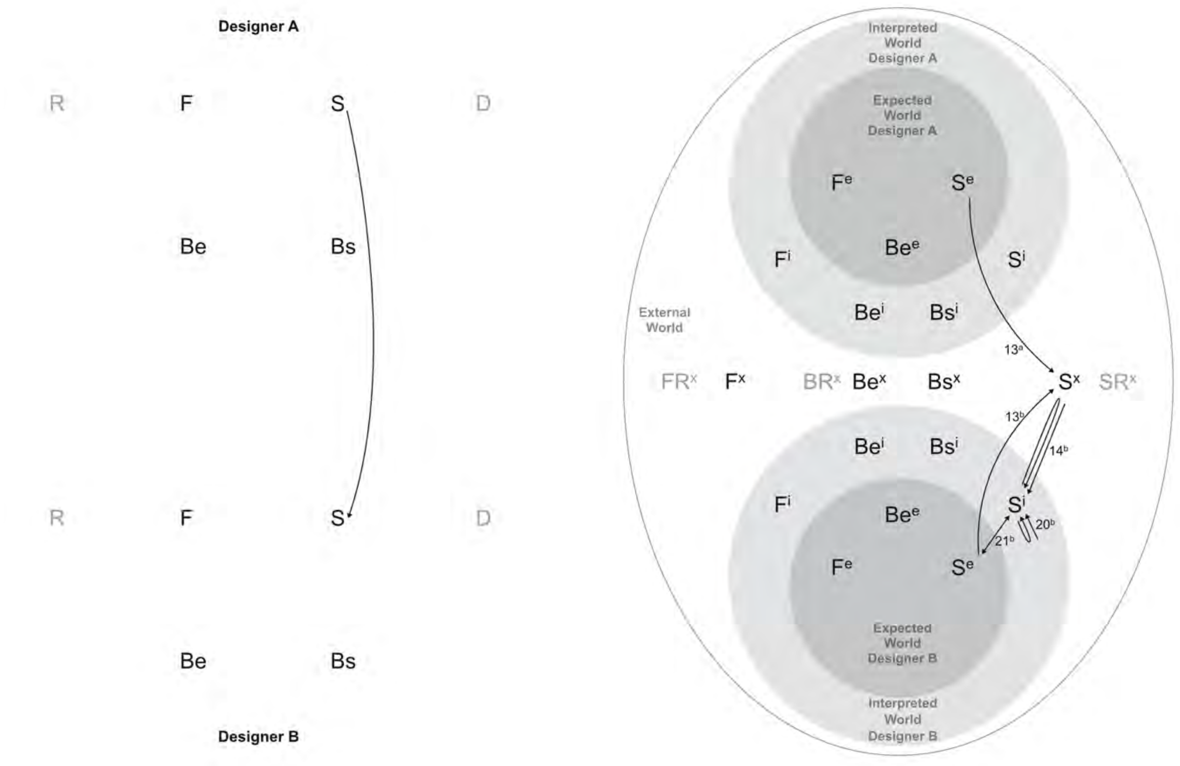


(a) (b)

Figure 13. (a) FBS co-evaluation, Be to Bs, (b) situated FBS co-evaluation, Be to Bs

3.8 Reformulation 1: co-construction of structure from structure

Reformulation 1 results in a change of structure (S) into another structure (S). In a co-design situation, Reformulation 1 implies that a designer creates another structure (S) from a structure generated by another designer (Figure 14). Designer A generates a structure in the external world (S^x) based on an expected structure set in his/her expected world (S^e) (process 13^b). Designer B interprets designer A's structure (S^x) into an interpreted structure (S^i) (process 14^b). The generated interpreted structure can be enhanced by a constructive memory process (process 20^b) and produces an expected structure in his/her expected world (S^e) (process 21^b). The expected structure (S^e) is then communicated into the external world into a structure (S^x) by designer B (process 13^b).

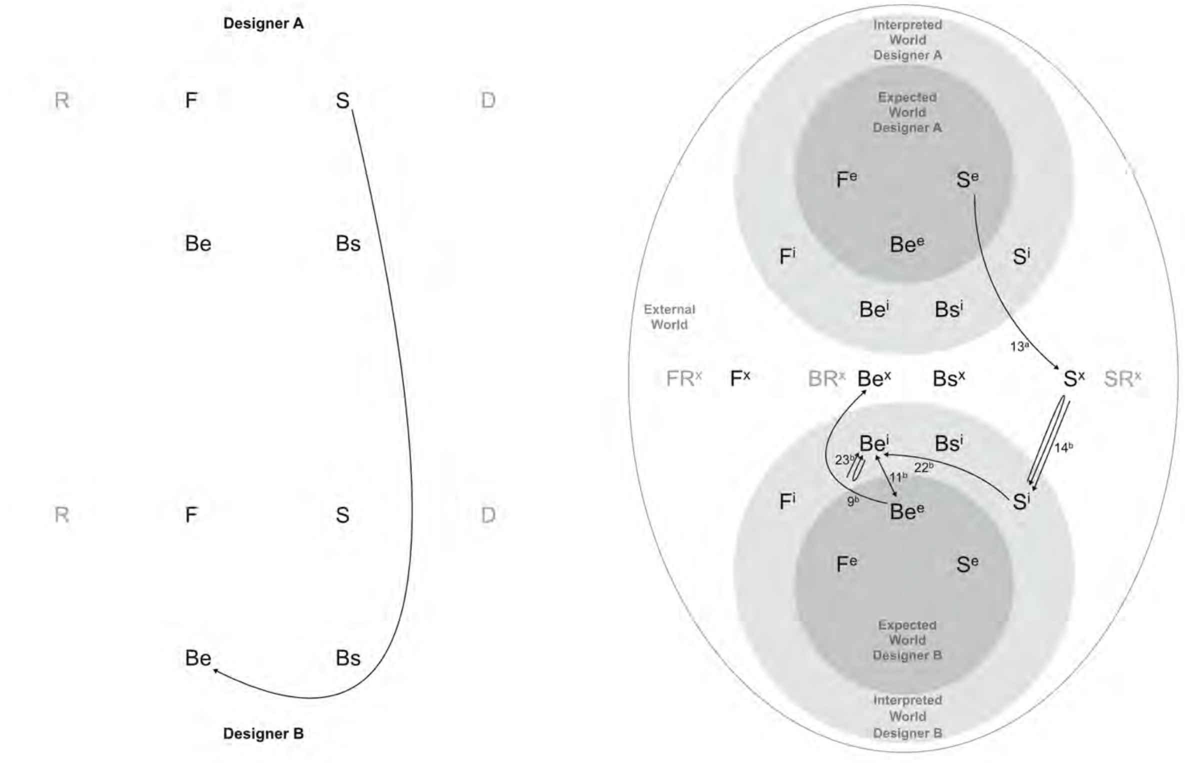


(a) (b)

Figure 14. (a) FBS Reformulation 1 by the co-construction of S from S, (b) situated FBS Reformulation 1 by the co-construction of S from S

3.9 Reformulation 2: co-construction of expected behavior from structure

The Reformulation 2 design process results in a change of the variables of an expected behavior based on a structure. In the co-design situation, a designer formulates the structure that the other designer interprets to reformulate an expected behavior (Figure 15). Designer A generates a structure in the external world (S^x) based on an expected structure set in his/her expected world (S^e) (process 13^a). Designer B interprets designer A's structure in the external world (S^x) into an interpreted structure (S^i) (process 14^b). This interpreted structure (S^i) reformulates an interpreted expected behavior (Be^i) (process 22^b) and can be enhanced by a constructive memory process (process 23^b) before producing an expected behavior (Be^e) in designer B's expected world (process 11^b). The expected behavior in the expected world is then communicated into the external world as an expected behavior (Be^x) by designer B (process 9^b).

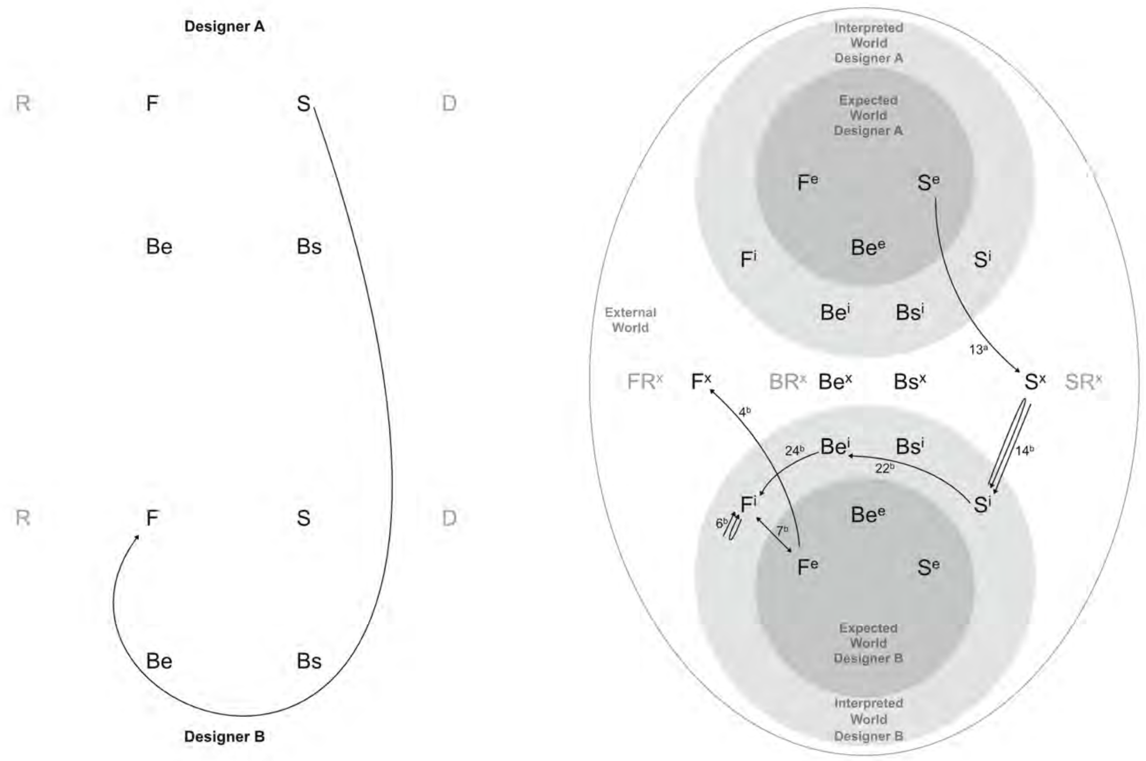


(a) (b)

Figure 15. (a) FBS Reformulation 2 by the co-construction of Be from S, (b) situated FBS Reformulation 2 by the co-construction of Be from S

3.10 Reformulation 3: co-construction of function from structure

Reformulation 3 design process expresses a reformulation of a function based on a structure. In a co-design situation, the first designer produces a structure that leads to a reformulation of a function produced by the second designer (Figure 16). Designer A formulates a structure in the external world (S^x) based on an expected structure (S^e) situated in his/her expected world (process 13^a). The external structure (S^x) is interpreted by designer B into an interpreted structure (S^i) (process 14^b), that generates an interpreted expected behavior (Be^i) (process 22^b), reformulated into an interpreted function (F^i) (process 24^b). Designer B's interpreted function (F^i) can be enhanced by a constructive memory process (process 6^b) before it produces an expected function in his/her expected world (F^e) (process 7^b). The expected function is externalized in the external world into a function (F^x) (process 4^b) by designer B.

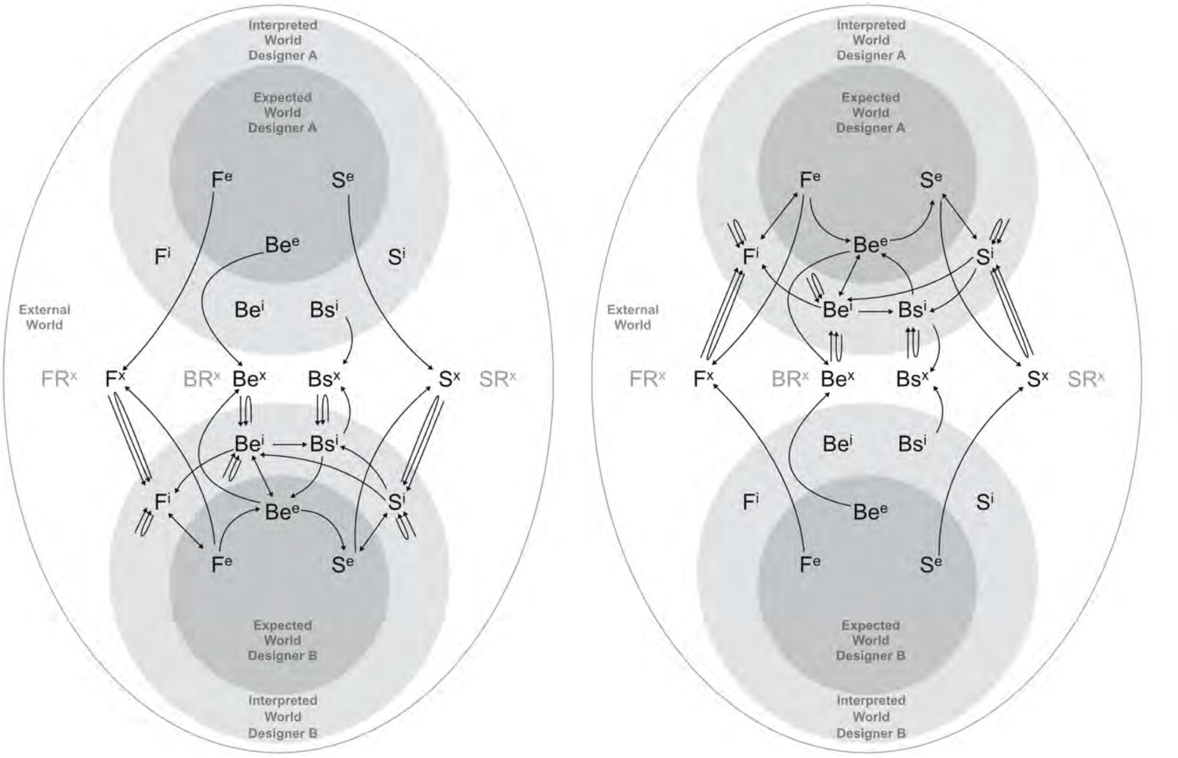


(a) (b)

Figure 16. (a) FBS Reformulation 3 by the co-construction of F from S, (b) situated FBS Reformulation 3 by the co-construction of F from S

3.11 Situated FBS model of co-design

The aggregation of all the co-constructed situated FBS processes (Figures 6 to 16) represent co-design processes initiated by designer A and continued by designer B within the FBS ontology description (Figure 17(a)). The proposed model is commutative, therefore all possible co-constructed situated FBS processes started by designer B and carried on by designer A can be represented symmetrically (Figure 17(b)).



(a) (b)

Figure 17. (a) Situated FBS co-construction of design processes from designer A to B, (b) and situated FBS co-construction of design processes from designer B to A

The overall representation of the situated FBS co-design model is a combination of the processes initiated by designer A and those initiated by designer B (Figure 18). Figure 18 looks complicated at first sight, but accounts for the complexity of cognitive design processes in a collaborative setting.

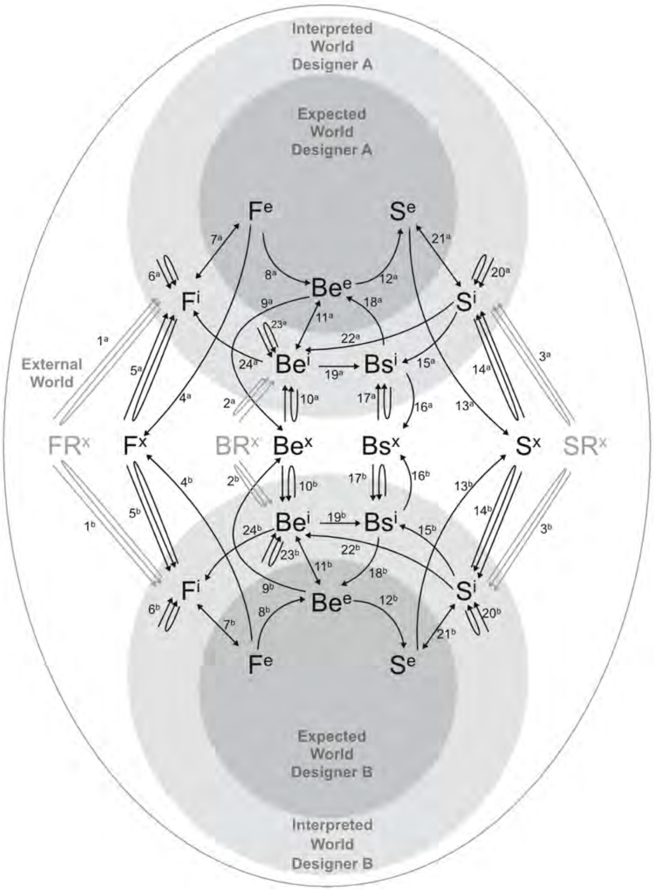


Figure 18. Situated FBS model of co-design processes

4 Using the situated FBS co-design model to represent empirical results: illustrated examples

The situated FBS co-design model is commutative, which means that designer A's actions are potentially equivalent to designer B's actions. However, due to the situatedness of the design activity, each designer will react differently to what their teammates do since they all have different expertise and past experiences. We highlighted a limit in previous studies on the assessment of co-design in their lack of fine-grained representation of team members' participation to the design activity. The situated FBS co-design model has a potential to illustrate team members differences regarding how they respond and interact with other teammates through shared external design representation. However, the representation of the overall co-design activity is maintained. To demonstrate the relevance of our model, we present multiple examples of its use to represent information from an engineering co-design session between two designers. The sample data used is taken from wider study of professional engineers who worked in teams of two and were asked to work on a window design task for an hour (see Gero & Song, 2018). A final sketch of the design was the output at the end of the session. Each session was video recorded for further analysis. The example was randomly picked from the sessions in that project to extract co-design behavior information from that session. The session had been previously transcribed and coded using the FBS design issues (Requirement, Function, expected Behavior, Structure, Behavior from structure and Description). All coded design issues sit in the external world, since they have to be externalized to be heard. Therefore, all coded design processes are defined in the FBS ontology framework, before they are mapped onto the situated FBS co-design model. Design processes were determined by examining sequential design issue transitions, making the results syntactic design processes (Kan & Gero, 2017). Each design issue was also coded with the speaker (designer A or designer B), so that co-constructed processes (from designer A to B, or from designer B to A) could be differentiated from individually constructed processes (from Designer A to himself and from Designer B to himself). A rich set of tools and methods to analyze design protocols can be exploited to represent data in our model (Kan & Gero, 2017). In the following, we provide a non-exhaustive set of examples showing formal displays of co-design behaviors. We focused on:

- the quantitative distribution of co-design processes;
- dominant co-design processes as indicated by their percentage occurrence;
- dominant co-design processes as indicated by the first order Markov model;
- problem/solution space transitions during a co-design session;
- a time base evolution of the dominant co-design processes over a session.

4.1 Example of the representation of the quantitative distribution of co-design processes

The co-design activity is sequenced by individual design and co-design moments. Twenty co-design processes were described in the situated FBS co-design model, that add to the previously described situated FBS design processes (Gero and Kannengiesser, 2004) and raises the number of possible processes to 42. The distribution of those 42 processes for our session example is shown in the bar graph in Figure 19. Individual design processes are represented in light grey and co-design processes are represented in dark grey (Figure 19).

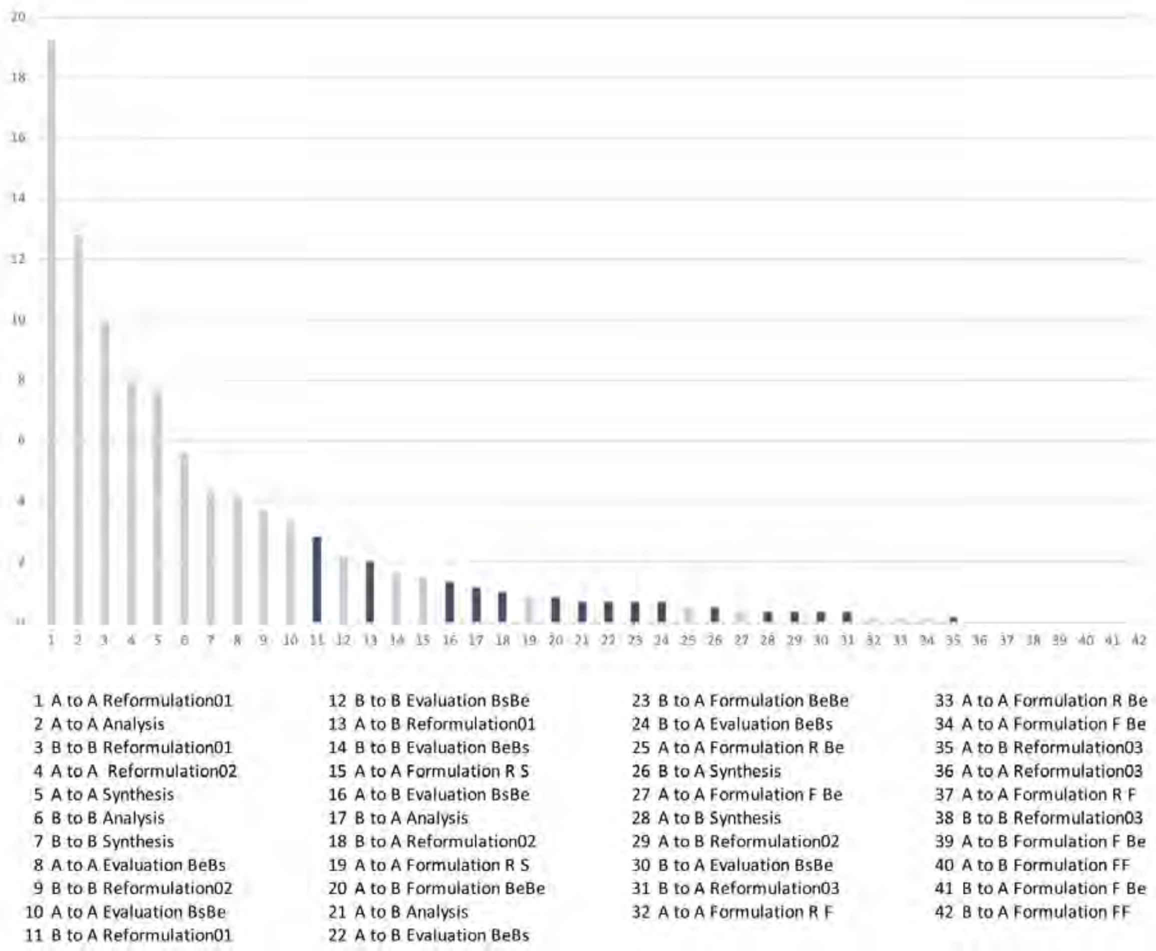


Figure 19. Distribution of design (light grey) and co-design processes (dark grey) for the engineering co-design session

The five dominant co-design processes from the engineering session are represented in our model in Figure 20. The overall co-design activity and each designer's dominant behavior during the session is qualitatively represented through the co-design model. The co-evolution of the problem/solution space (Dorst & Cross, 2001; Maher & Poon, 1996) has formerly been studied in co-design, although the team was represented as a single entity (Valkenburg, 2000; Valkenburg & Dorst, 1998). The transition from the problem space to the solution space, or inversely, can be described in our model, Figure 20. In the FBS ontology, function (F) and expected behavior (Be) are part of the problem space, while behavior derived from structure (Bs) and structure (S) are part of the solution space. Based on this model, we can qualitatively see processes going from the problem space to the solution space (synthesis and evaluation, ie, Be to Bs) and those from the solution space to the problem space (reformulation of Be based on S). The model also shows that some processes occur in a single space like formulation of expected behavior (Be) or the reformulation of structure (S).

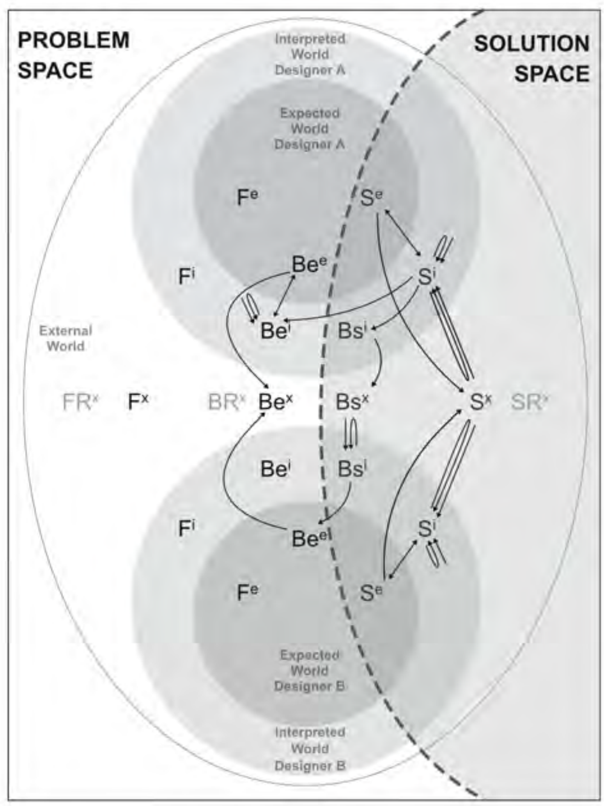


Figure 20. Representation of the dominant co-design processes for the engineering co-design session

In this example, both designer A's and B's participation in the co-design activity in aggregate is approximately equal but not identical (Figure 20). They both formulate utterances to which the other designer responds Designer A analyses designer B's structure (S), to reformulate designer B's structure (S) into another structure (S) or to modify expected Behavior (Be) variables from designer B's structure (S). Designer B also reformulates designer A's structure (S) into other structure (S) and evaluates designer A's formulation of Behavior derived from structure (Bs). The co-design activity either stays within the solution space or within the problem with only some movement from the solution space to the problem space.

We can gain a qualitative understanding of the co-design activity from these diagrammatic depictions. For example, there are no processes in these dominant co-design processes in Figure 20 that move between the problem and solution spaces.

Design behavior changes throughout a session. The model can also represent the dynamics of the session, showing a temporal evolution of dominant co-design processes throughout the session, which complements the static quantitative representation of the whole session. We divided the co-design engineering session into five parts and looked at the dominant co-design processes evolution from the first quintile (Figure 21) to the fourth quintile (Figure 22).

The co-design activity at the beginning of the session contains processes that are not present later in the session such as the reformulation of Function (F) from design structure (S) and the synthesis of expected Behavior (Be) into design structure (S). Designer A is more in the co-design activity active than designer B at the beginning of the session (Figure 21). In the fourth quintile designer's participation to the co-design activity is more balanced (Figure 22).

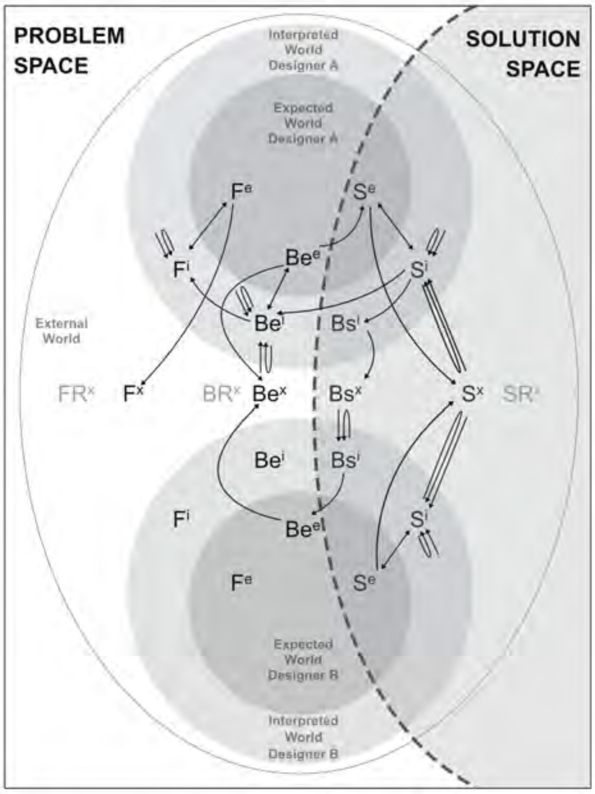


Figure 21. Representation of the main co-design processes in the first quintile of the engineering co-design session

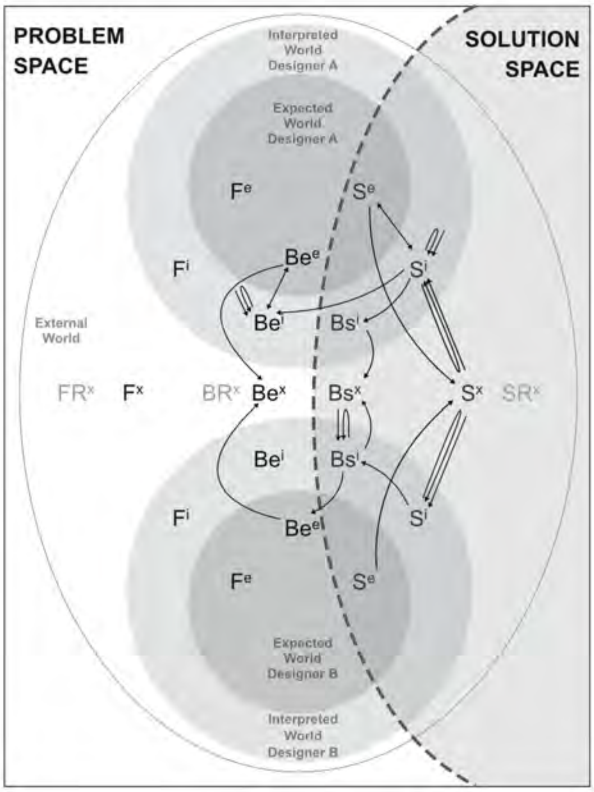


Figure 22. Representation of the dominant co-design processes in the fourth quintile of the engineering co-design session

4.2 Example of the representation of the dominant transitions in co-design processes

The distribution of co-design processes illustrates the magnitude of each process. Complementary information about the co-designers' behavior is provided by generating a Markov model of the processes. The Markov model shows the probability of going from one given state to another state, in our case from a design issue formulated by one designer to a design issue expressed by the same designer or the other designer (see Kan & Gero, 2017; Milovanovic & Gero, 2018; Yu & Gero, 2016 for examples). The significance of the transitions is not taken into account, as the first order Markov model provides a measure of the probability and does not keep the quantitative distribution of each design issue. Co-design processes identified with a probability equal to or higher than 0.17 (twice the value of the random transition probability) in the engineering session are represented in Figure 23.

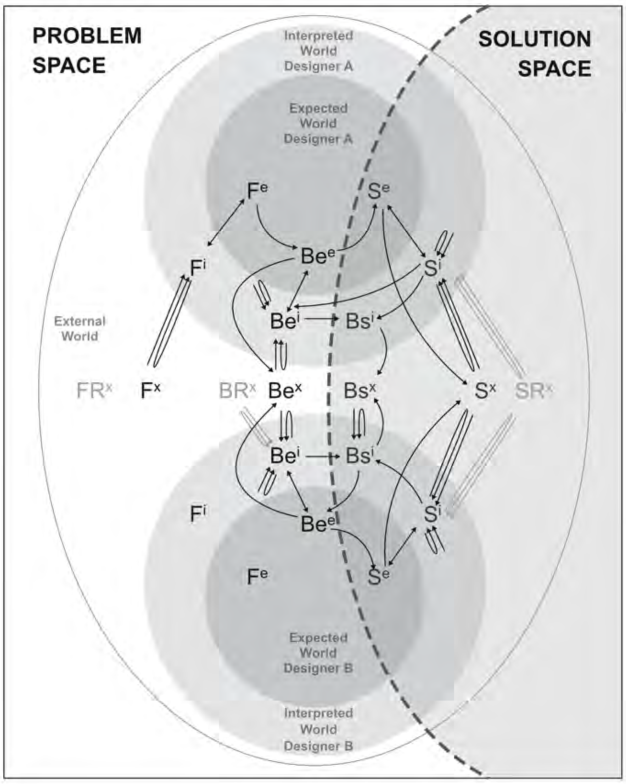


Figure 23. Representation of dominant situated FBS co-design processes from the first order Markov model

From the Markov model of the co-design activity in Figure 23 we can observe that the probability one designer working in one space of having their co-designer respond in the other space is low across the entire design session.

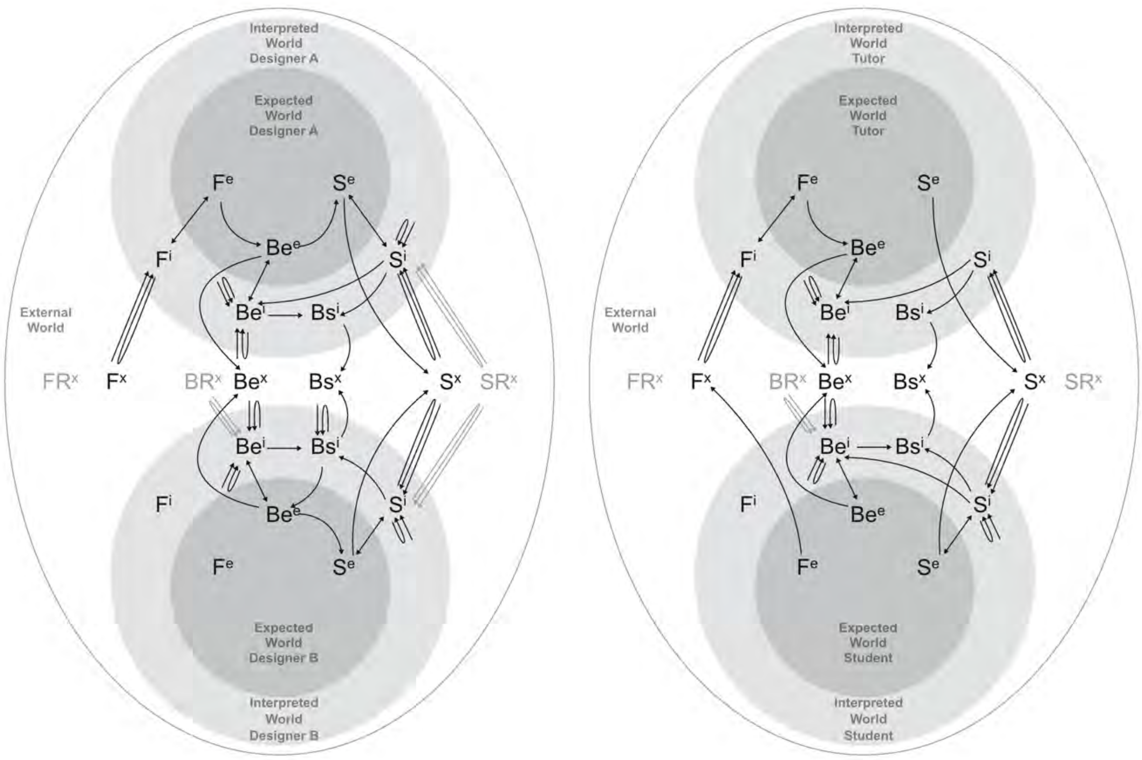
5 Discussion

The examples above show possible applications of our model to represent quantitative and qualitative empirical data extracted from protocol analysis using the FBS ontology coding scheme. The situated FBS co-design model gives a clearer understanding of the occurrence of cognitive actions during design sessions. It considers the session as a unit but preserves a fine-grained representation of each designer's participation and interaction with each other. A particular significance of our model is its adaptability to diverse situations, and its scalability as it can grow to represent more complex co-design situations.

5.1 Adaptability

Empirical studies delineated design behavior commonalities and divergence depending on the designers' domain (Gero & Jiang, 2016; Gero & Kannengiesser, 2014). Moreover, the communication settings in co-design (Tang et al., 2011), or the use of different design representation environments (Yu & Gero, 2016), can affect design behaviors. To compare different design situations, a baseline is required. The FBS ontology and the proposed co-design model provide a common framework and a new perspective to study similarities and differences in co-design situations.

To illustrate our model's adaptability to different situations, an example of the comparison of two design protocols is given: an engineering design session (same protocol as in Section 4) and an architectural critique session in a pedagogic environment. The dominant co-design processes, indicated by the first order Markov model, and the participants' interactions are different between the engineering session, Figure 24(a), and the architectural critique session, Figure 24(b). Both designers in the engineering session are focused on formulating expected behavior (Be), synthesizing it into design structure (S) and reformulating it into other design behavior (Be and Bs). On the other hand, in the architectural critique, more cognitive effort was put into formulating expected behavior (Be) from design function (F), reformulating design behavior (Be) from design structure (S) and analyzing design behavior (Bs) from existing structure (S). The dominant Markov pattern we found in these two sessions could be due to the domain or the goals behind the session (design versus pedagogy). The explanation for these differences is not explored here.



(a) (b)

Figure 24. (a) Dominant situated FBS co-design Markov processes for the engineering design session, and (b) dominant situated FBS co-design Markov processes for the architectural critique session

5.2 Scalability

The shift from individual design to collaborative design, either remote or collocated, fostering a large number of designers working together, makes it necessary to investigate the scalability of our co-design model. Teammates communicate through the external world, which contains the design Requirement (R), the design Function (F), the design Behavior (B) and the design Structure (S). There is one instance of the design artefact in the external world at any time being focused on, so that the increasing number of designers does not increase the number of interactions exponentially. Design interactions take place through the funnel of the external design representation themselves (R^x, F^x, Bx and S^x). Figure 25 presents a representation of a situated FBS co-design model in a team of four designers. The FBS instances in each designer's interpreted and expected world is simplified under the label X^i and X^e for visual representation purposes. The model can be expanded to an unlimited amount of designers, and is able to include team systems and subsystems that represent the complex organizations of designers working on the same artefact.

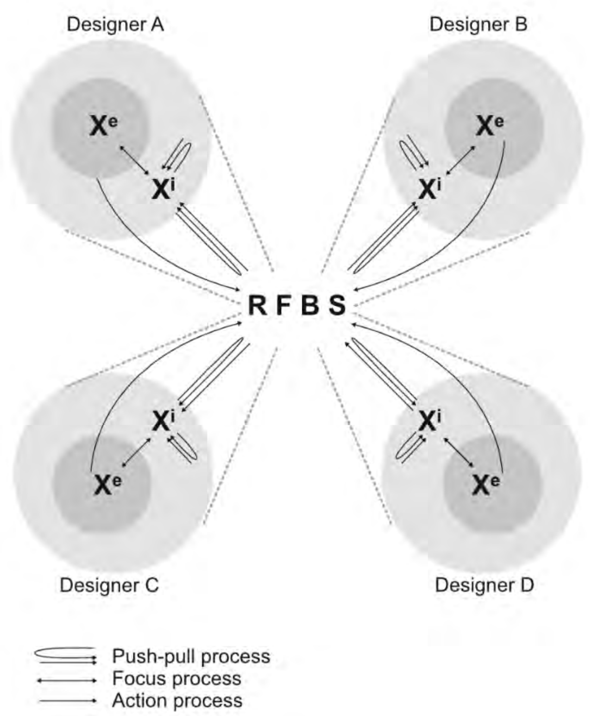


Figure 25. Situated FBS co-design processes for a team of four designers.

In Figure 26, we show how the co-design model develops while increasing the number of teams, and representing the diversity of team interactions. In this example, three teams work together with different level of interactions. All teams co-design on the overall design object represented by the R^x, F^x, B^x, $S^{x\ 1,2,3}$ instance. Teams 2 and 3 also work on a sub-part part of the design object that has another instance (R^x, F^x, B^x, $S^{x\ 2,3}$) in the external world.

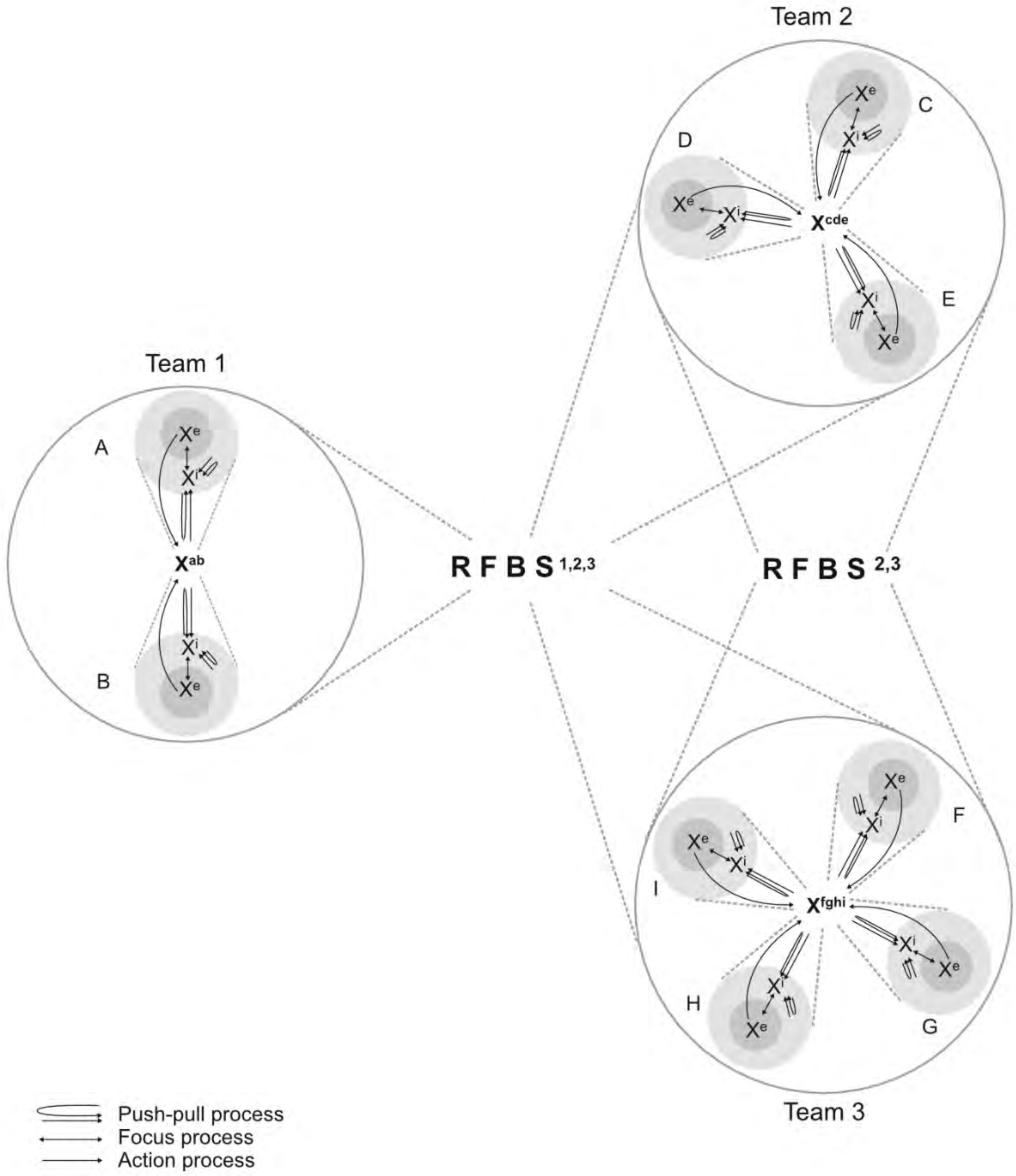


Figure 26. Situated FBS co-design processes for multiple teams each with a varying number of designers, where Team 1 interacts with Teams 1, and 3 while Teams 2 and 3 also separately interacts with each other.

6 Conclusion

The main drawback of most existing co-design models is their lack of precision in representing designers' participation and interactions with the design situation. Moreover, the situatedness of co-design is not addressed as internal cognitive thinking processes are not represented. To deal with that knowledge gap we developed a situated co-design model within an existing design ontology: the Function Behavior Structure ontology. A step-by-step description of each situated FBS co-design process provides an overall development of the model. The significance of the model is its capacity to describe co-design cognitive design processes, looking at the team's overall behavior through their individual behaviors and each designer's participation in the design activity. The graphical representation of the model also provides a qualitative representation of team interactions with the design artefact that is easy to visualize.

Through examples, we demonstrated the utility of the model to represent quantitative commensurable information on cognitive co-design processes. We showed examples of the dominant co-design processes based on their distributions, dominant co-design processes based on their occurrence and on their probability of occurrence as indicated by a first order Markov model of the segmented protocol and the evolution of the team's co-design behavior over a design session. One goal in the development of such a model is to provide an adaptable and scalable co-design model, which can benefit empirical research on co-design. The situated FBS co-design model provides a baseline to compare different design situations that depend on the design field, communication media setting, design tools or design strategies used, to name a few. The scalability of the model is an essential factor to consider, since co-design can involve multiple team members working on the same design artefact and teams of teams as in systems design (for example in the aerospace industry). The model can expand to any number of team members and can adapt to a system-like organization.

This model lends itself to the empirical exploration of a wide variety of design team behaviors such as gender diversity effects in teams, the development of de facto sub-teams in formally constituted teams, and multiple teams behavior within systems design. It can be used as a theoretical model on which to build computational models such as in co-creation between a human and a computational, situated, cognitive agent or between multiple computational, situated, cognitive agents.

Acknowledgement

To come

References

Chiu, M.-L. (2002). An organizational view of design communication in design collaboration. *Design Studies*, *23*(2), 187–210. https://doi.org/10.1016/S0142-694X(01)00019-9

Clark, H. H., & Brennan, S. E. (1991). Grounding in communication. In L. B. Resnick, J. M. Levine, & S. D. Teasley (Eds.), *Perspectives on socially shared cognition* (American Psychology Association, pp. 127–149). Washington.

Clark, H. H., & Wilkes-Gibbs, D. (1986). Referring as a collaborative process. *Cognition*, *22*, 1–39.

Cross, N., & Clayburn Cross, A. (1995). Observations of teamwork and social processes in design. *Design Studies*, *16*(2), 143–170. https://doi.org/10.1016/0142-694X(94)00007-Z

Darses, F. (2009). Résolution collective des problèmes de conception. *Le travail humain*, *72*(1), 43. https://doi.org/10.3917/th.721.0043

Darses, F., Détienne, F., Falzon, P., & Visser, W. (2001). *COMET. A method for analysing collective design processes* (No. RR-4258). INRIA.

Darses, F., & Falzon, P. (1994). La conception collective : une approche de l'ergonomie cognitive. In G. de Terssac & E. Friedberg (Eds.), *Coopération et Conception* (p. 12). Toulouse, France.

Dorst, K., & Cross, N. (2001). Creativity in the design process: co-evolution of problem–solution. *Design Studies*, *22*(5), 425–437. https://doi.org/10.1016/S0142-694X(01)00009-6

Dorta, T., Kalay, Y., Lesage, A., & Pérez, E. (2011). Design conversations in the interconnected HIS. *International Journal of Design Sciences and Technology*, *18*(2), 65–80.

Dorta, T., Lesage, A., Pérez, E., & Bastien, J. C. (2011). Signs of collaborative ideation and the hybrid ideation space. In T. Taura & Y. Nagai (Eds.), *Design Creativity 2010* (pp. 199–206). London: Springer. Retrieved from https://link.springer.com/chapter/10.1007/978-0-85729-224-7_26

Ericsson, K. A., & Simon, A. H. (1984). *Protocol Analysis: Verbal reports as data*. MIT Press.

Eris, O., Martelaro, N., & Badke-Schaub, P. (2014). A comparative analysis of multimodal communication during design sketching in co-located and distributed environments. *Design Studies*, *35*(6), 559–592. https://doi.org/10.1016/j.destud.2014.04.002

Finke, R. A., Ward, T. B., & Smith, S. M. (1992). *Creative cognition: theory, research, and application*. Cambridge: MIT Press.

Gero, J. S. (1990). Design prototypes: a knowledge representation schema for design. *AI Magazine*, *11*(4), 26–36. https://doi.org/10.1609/aimag.v11i4.854

Gero, J. S., & Jiang, H. (2016). Exploring the design cognition of concept design reviews using the FBS-Based protocol analysis. In R. S. Adams & J. A. Siddiqui (Eds.), *Analyzing design review conversations*. West Lafayette, Indiana: Purdue University Press.

Gero, J. S., & Kannengiesser, U. (2004a). Modelling expertise of temporary design teams. *Journal of Design Research*, *4*(2), 174–184. https://doi.org/10.1016/j.destud.2003.10.010

Gero, J. S., & Kannengiesser, U. (2004b). The situated function–behaviour–structure framework.

Design Studies, *25*(4), 373–391. https://doi.org/10.1016/j.destud.2003.10.010

Gero, J. S., & Kannengiesser, U. (2008). An ontological account of Donald Schön’s reflection in designing. *International Journal of Design Sciences and Technologies*, *15*(2), 77–90.

Gero, J. S., & Kannengiesser, U. (2014). Commonalities across Designing: Evidence from Models of Designing and Experiments. *Design Computing and Cognition’12*, 285–302.

Gero, J. S., & Song, T. (2018). Decomposition/Recomposition Design Behavior of Student and Professional Engineers: A Pilot Study.

Gibson, C. B. (2001). From knowledge accumulation to accommodation: cycles of collective cognition in work groups. *Journal of Organizational Behavior*, *22*(2), 121–134. https://doi.org/10.1002/job.84

Goldschmidt, G. (1990). Linkography: assessing design productivity (pp. 291–298). Presented at the Proceedings of the Tenth European Meeting on Cybernetics and Systems Research, Singapore: World Scientific.

Goldschmidt, G. (1995). The designer as a team of one. *Design Studies*, *16*(2), 189–209. https://doi.org/10.1016/0142-694X(94)00009-3

Goldschmidt, G. (2014). *Linkography, Unfolding the design process*. MIT Press.

Hamraz, B., Caldwell, N. H. M., Ridgman, T. W., & Clarkson, P. J. (2015). FBS Linkage ontology and technique to support engineering change management. *Research in Engineering Design*, *26*(1), 3–35. https://doi.org/10.1007/s00163-014-0181-9

Kan, J. W. T., & Gero, J. S. (2017). *Quantitative Methods for Studying Design protocols*. Springer.

Klimoski, R., & Mohammed, S. (1994). Team Mental Model: Construct or Metaphor? *JOURNAL OF MANAGEMENT*, *20*(2), 35.

Kvan, T. (2000). Collaborative design: what is it? *Automation in Construction*, *9*(4), 409–415. https://doi.org/10.1016/S0926-5805(99)00025-4

Lawson, B. (2004). Schemata, gambits and precedent: some factors in design expertise. *Design Studies*, *25*(5), 443–457. https://doi.org/10.1016/j.destud.2004.05.001

Maher, M. L., & Poon, J. (1996). Modeling design exploration as co-evolution. *Computer-Aided Civil and Infrastructure Engineering*, *11*(3), 195–209. https://doi.org/10.1111/j.1467-8667.1996.tb00323.x

Masclet, C., & Boujut, J.-F. (2010). Using situated FBS to model design interactions in a distant synchronous collaborative situation. In *DESIGN2010* (p. 10).

Milovanovic, J., & Gero, J. (2018). Exploration of cogntivie design behavior during design critiques. In *DESIGN2018* (p. 12). Dubrovnik, Croatia.

Mohammed, S., Ferzandi, L., & Hamilton, K. (2010). Metaphor No More: A 15-Year Review of the Team Mental Model Construct. *Journal of Management*, *36*(4), 876–910. https://doi.org/10.1177/0149206309356804

Ostergaard, K. J., & Summers, J. D. (2009). Development of a systematic classification and taxonomy of collaborative design activities. *Journal of Engineering Design*, *20*(1), 57–81. https://doi.org/10.1080/09544820701499654

Pauwels, P., Strobbe, T., & De Meyer, R. (2015). Analysing how constraints impact architectural decision-making. *International Journal of Design Sciences and Technology*, *21*(1), 83–111.

Pirola-Merlo, A., & Mann, L. (2004). The relationship between individual creativity and team creativity: aggregating across people and time. *Journal of Organizational Behavior*, *25*(2), 235–257. https://doi.org/10.1002/job.240

Sauder, J., & Jin, Y. (2016). A qualitative study of collaborative stimulation in group design thinking. *Design Science*, *2*. https://doi.org/10.1017/dsj.2016.1

Schön, D. (1983). *The reflective practitioner: How professionals think in action*. London: Temple Smith.

Schön, D. (1992). Designing as reflective conversation with the materials of a design situation. *Research in Engineering Design*, *3*(3), 131–147. https://doi.org/10.1007/BF01580516

Sonnenburg, S. (2004). Creativity in Communication: A Theoretical Framework for Collaborative Product Creation. *Creativity and Innovation Management*, *13*(4), 254–262. https://doi.org/10.1111/j.0963-1690.2004.00314.x

Stempfle, J., & Badke-Schaub, P. (2002). Thinking in design teams - an analysis of team communication. *Design Studies*, *23*(5), 473–496. https://doi.org/10.1016/S0142-694X(02)00004-2

Tang, H. H., Lee, Y. Y., & Gero, J. S. (2011). Comparing collaborative co-located and distributed design processes in digital and traditional sketching environments: A protocol study using the function–behaviour–structure coding scheme. *Design Studies*, *32*(1), 1–29. https://doi.org/10.1016/j.destud.2010.06.004

Valkenburg, R. (2000). *The reflective practice in product design teams*. Delft University of Technology, Delft, Netherlands.

Valkenburg, R., & Dorst, K. (1998). The reflective practice of design teams. *Design Studies*, *19*(3), 249–271.

Wiltschnig, S., Christensen, B. T., & Ball, L. J. (2013). Collaborative problem–solution co-evolution in creative design. *Design Studies*, *34*(5), 515–542. https://doi.org/10.1016/j.destud.2013.01.002

Yu, R., & Gero, J. S. (2016). An empirical basis for the use of design patterns by architects in parametric design. *International Journal of Architectural Computing*, *14*(3), 289–302.

https://doi.org/10.1177/1478077116663351