The Situated Function-Behavior-Structure Co-Design Model

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This paper 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.

Keywords: collaborative design; design models; design cognition; design theory

Collaboration in design has become essential with the growing complexity of designed artefacts, a higher need for innovation and an increasing demand for time efficiency. In collaborative design, teams, which involve multiple actors with different backgrounds and levels of expertise, have to work simultaneously on a unique designed artefact. 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 et al., 2001; Dorta et al., 2011; Stempfle & Badke-Schaub, 2002; Valkenburg & Dorst, 1998; Wiltschnig et al., 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 evaluation. 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), and the impacts of alternative media environments on co-design (Eris et al., 2014; Tang et al., 2011).

The frameworks used to analyze co-design are mostly categorical descriptions 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. 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; and
- 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 paper 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, 2004), adapted to a multiple designer 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, 2004).

The strength of our model is twofold. First, it builds on a widely used ontology that is design domain independent and is used in many design disciplines: architecture (Yu & Gero, 2016; Milovanovic & Gero, 2018), engineering (Hamraz et al., 2015; Masclet & Boujut, 2010), and software design (Hofmeister, et al, 2007), amongst others. Bott and Mesmer (2019) used it to code over 10,000 hours of designing in an aerospace company. Second, it provides a framework to analyze co-design protocols and graphically display commensurable quantitative and qualitative results inferred from the protocol analysis. Similar to the FBS ontology, the sFBS co-design model is independent of design domain and the design context. 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, which make it independent of design team size.

In the first section of this paper, we present some earlier frameworks and models used to analyze the co-design activity. The second section describes the FBS ontology in which our model is developed. The development of the situated FBS co-design model for the two-designer case is the focus of the third section. The last part of the paper discusses the significance of the sFBS co-design model in terms of its potential utility.

1. Co-designing: frameworks and models

In co-design, 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, 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 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 team members. 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 (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, they propose two levels of coding design conversations: design actions like generating, informing and evaluating and 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). These empirical case studies analyze and measure team design activities as a whole, without 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 to analyze co-ideation loops.

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). In this section, we will present a brief summary of some existing co-design models. We selected models that relate to the model we develop in Section 3.

1.2.1 Team process models

Chiu (2002) proposed a four-stage loop model of collaborative design resulting from 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 was proposed by Sonnenburg (2004), which integrates co-occurrences, interrelations and feedback loops within each of the eight steps such as preparation, illumination and verification. These models can be synthesized by mapping Gibson's (2001) model of collective cognition in teamwork to a collaborative design activity, Figure 1. This model includes four steps: accumulation; interaction; examination; and accommodation.

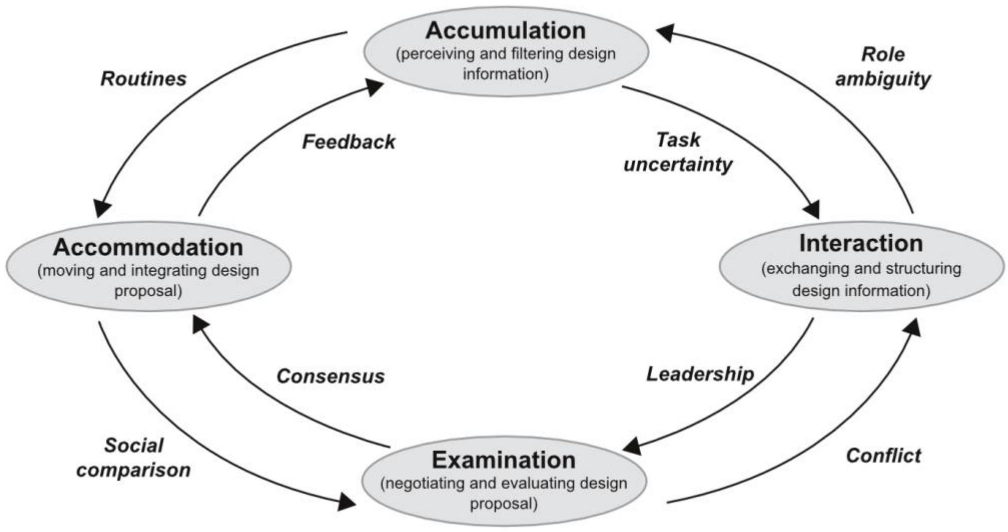


Figure 1. Process model of co-design, authors' interpretation, based on Gibson's (2001) model of collective cognition

1.2.2 Team interaction models

Sauder & Jin (2016) proposed a bridge between studies of individual creative cognition and group creativity. Their study focused on team interactions with the design situation and interactions between team members. They highlighted the drawback of team interaction models that consider individuals' creativity as a black-box. They 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.

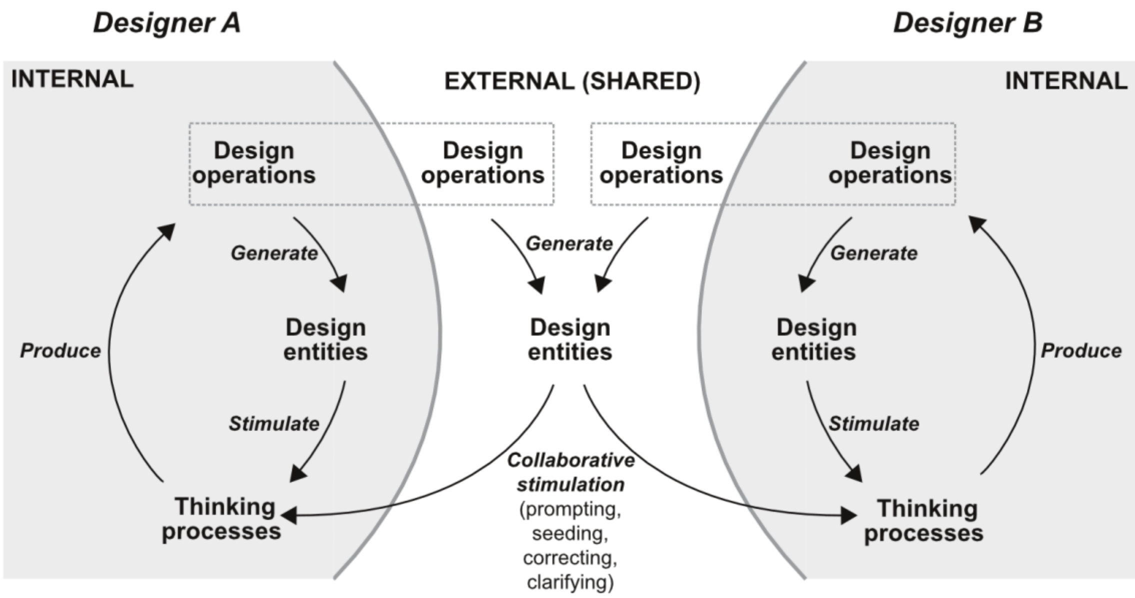


Figure 2. Collaborative thought stimulation, authors' interpretation based on Sauder & Jin (2016)

1.2.3 Limits

Team process models have the potential to display how design-related actions and teams' social behavior intertwine. The major limitation 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 uses 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 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 for 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 at a personal and social level, 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, client or regulation 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 is the production of any 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).

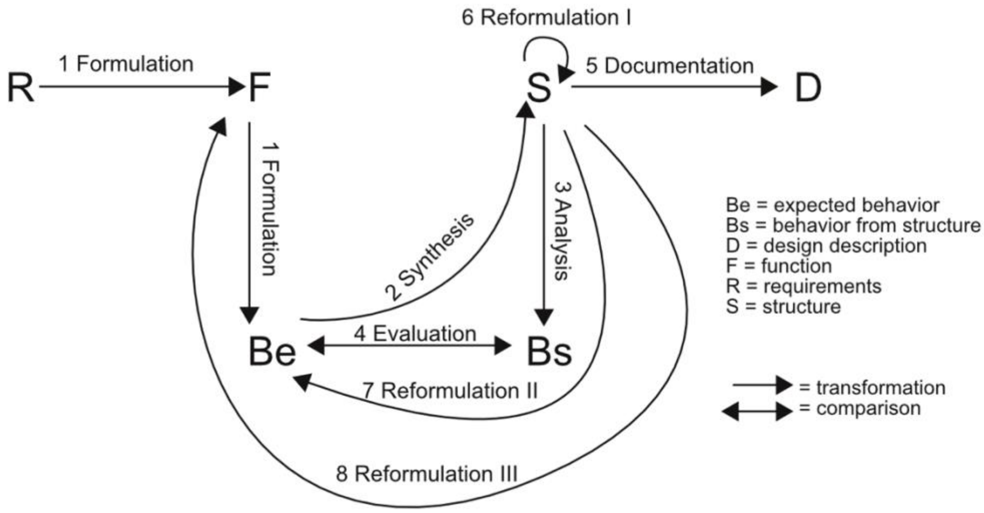


Figure 3. FBS framework showing design issues and design processes (based on Gero, 1990)

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). Each design situation is unique and each designer will react differently to it. The situated FBS framework is a cognitively articulated version of the FBS ontology that combines the FBS design processes with four cognitive processes: interpretation, constructive memory, focus and action (Gero & Kannengiesser, 2004). Three distinct worlds are identified in the situated FBS: the external world, the interpreted world and the expected world, which is part of the interpreted 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 perception, which is based on each individual's 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).

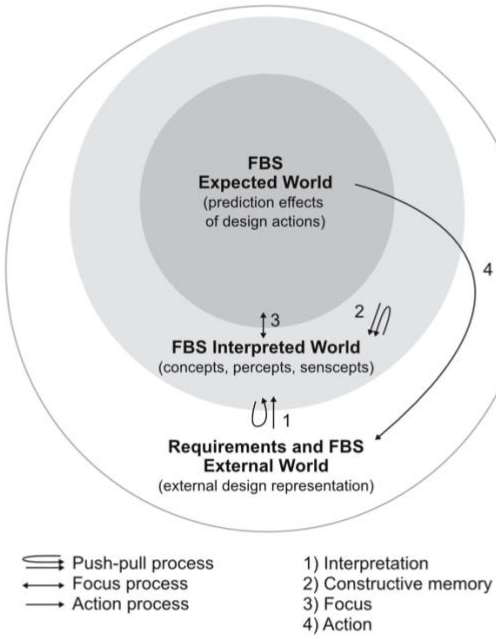
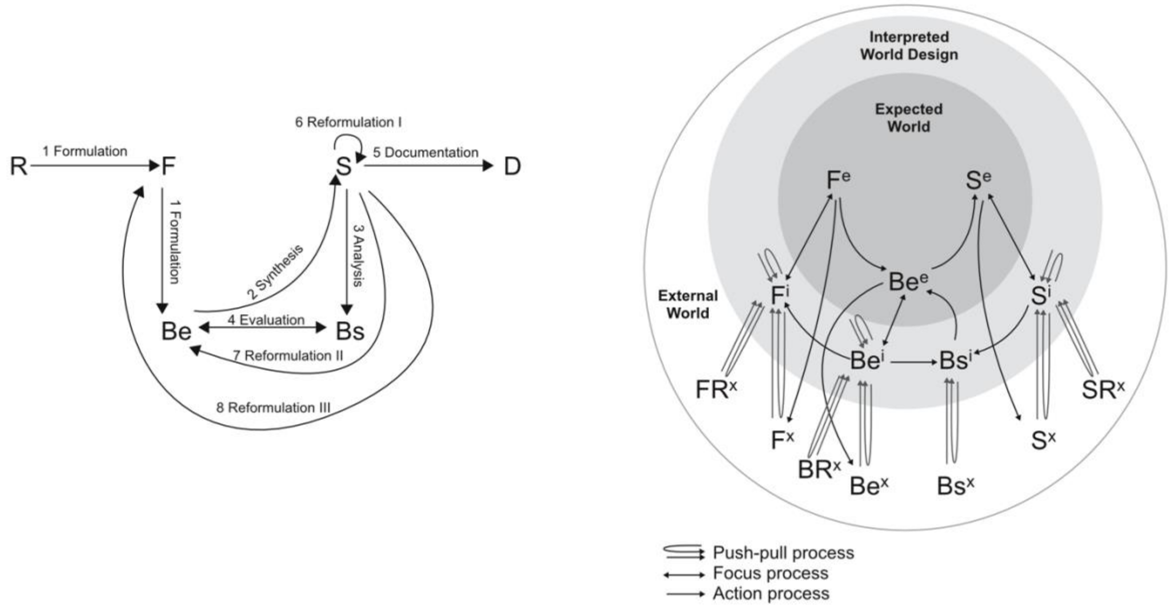


Figure 4. Situated design framework (based on Gero and Kannengiesser 2004)

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, 2004). This framework is 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 the situated FBS, Figure 5(b), seven design issues sit in the external world: Requirement related to function (FR^x), Requirement related to behavior (BR^x), Requirement related to structure (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). The situated FBS framework is a cognitively rich articulation of the FBS ontology.



(a) (b)

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

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, by a spatial-action language (Schön, 1983) through a combination of sketches, models, verbal utterances and gestures. They aim at co-constructing a design proposition to address a given design task. Each designer formulates design issues, expressing their individual views on the situation, that will affect their own and the other designer's cognitive processes. Each designer's personal design prototypes or schemata are related to their own experiences, and cultural and social background. To offer a better understanding of how co-designing functions, that takes into account the social and personal situatedness of co-designing, we developed a situated FBS co-design model to represent co-designing activity. Design processes in the interpreted and expected worlds integrate the personal level of the notion of situatedness. Design processes that sit at the interface between those worlds and the external world encapsulate the social level of design situatedness and represent designers' interactions with each other through external design representations defined as an instance of FBS, either verbal, gestural, graphical or model.

In the following, we describe a step-by-step development of the situated FBS co-design model. The proposed model is a cognitive articulation of the FBS ontology that shows how ontological co-design processes are mapped onto the situated FBS model. The FBS ontology describes design knowledge and design processes, therefore its co-design extension describes co-designing at a design-task level. 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, 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. For a better understanding of how our model unfolds, we will take an example of a two-person team designing a reading room for a library formulating the following FBS descriptions:

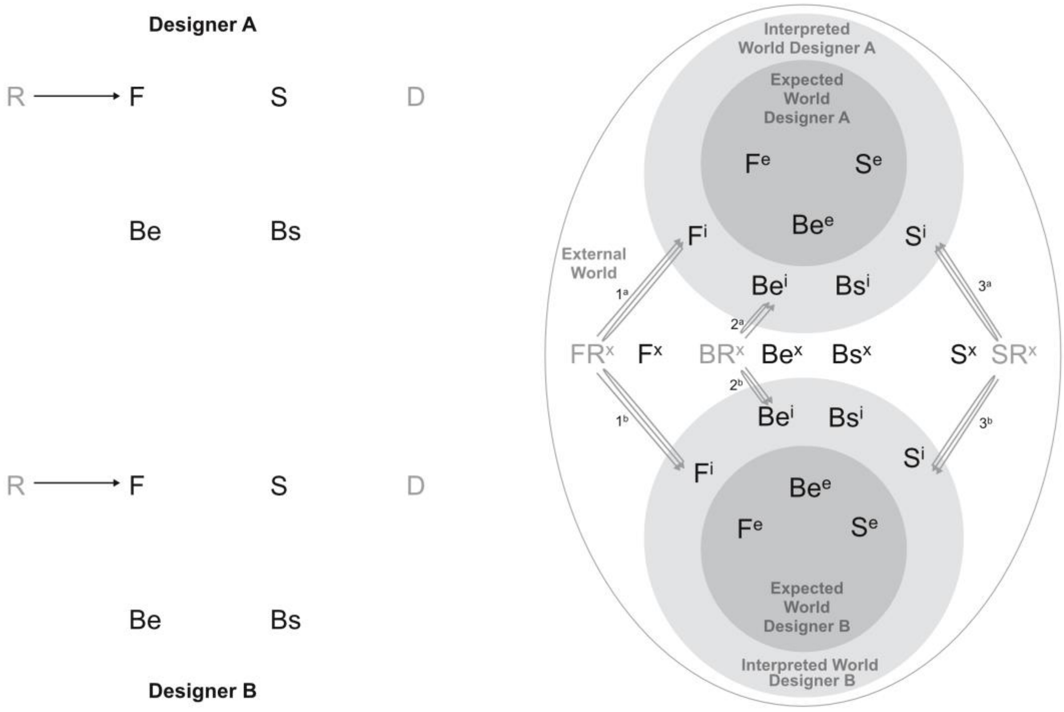
- Functions (F) such as "increase reading conditions", "enhance room atmosphere" or "connect to nature".
- Behaviors, expected (Be) or from current structures (Bs) such as "control light glare that dazzles readers" or "adjust transition and access from the reading room to adjacent spaces".

- Structures (S) such as "a horizontal window opening", "wavy ceilings" or "curved conic skylight monitors".

In the next section, we will go through the construction of each of the situated FBS co-design model processes. We will show the detailed development of the model connecting the following FBS design processes: Formulation, Synthesis, Analysis, Evaluation, Reformulation 1, Reformulation 2 and Reformulation 3, from the FBS ontology to the co-design model.

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 (F) into an expected Behavior (Be), Figure 7(a). In the situated FBS framework, requirements sit in the external world and are subdivided into three types, requirement related to 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 (R) is external to both designers (processes 1^a, 1^b, 2^a, 2^b, 3^a, 3^b in Figure 6(b)). Processes named x^a refer to designer A whereas processes named x^b refer to designer B. For instance, the requirements for designing a window for a library can be interpreted by designer A through the Function (F) of increasing reading conditions, whereas designer B can interpret it through the Function (F) of connecting the building to nature.

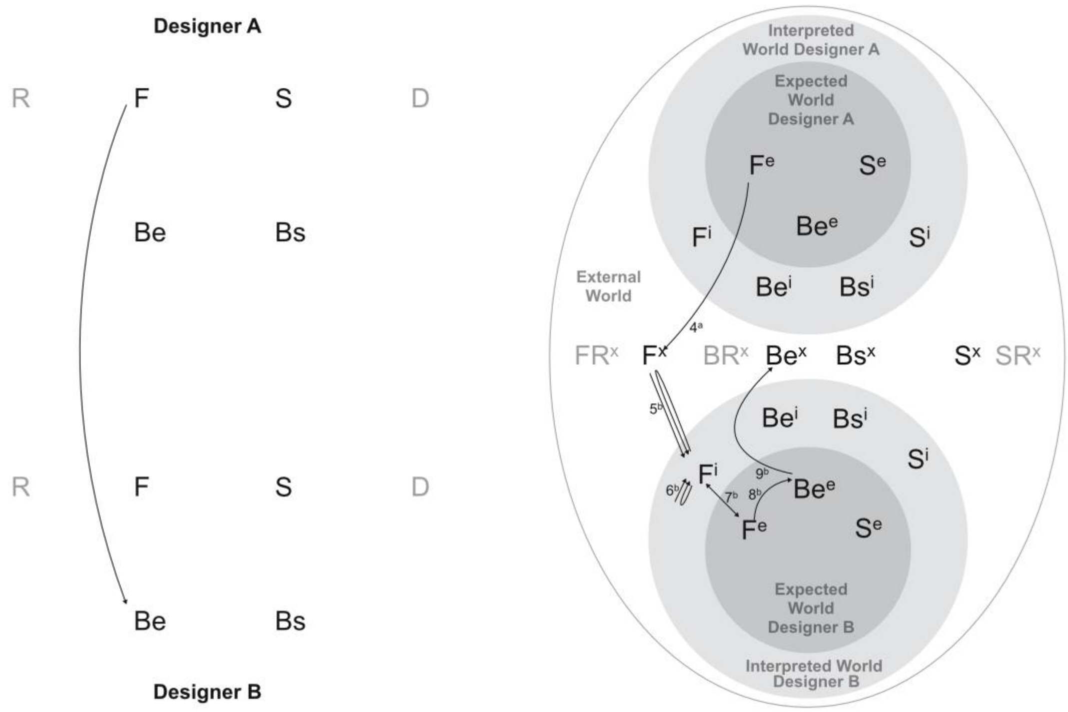


(a) (b)

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) can be co-constructed between two designers, Figure 7. 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), for example by expressing the importance of providing diffuse light in the library. 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), referencing with Designer's B past design experiences. 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 (Bex) (process 9^b). Designer B can suggest that they can play on windows orientations and arrangements.



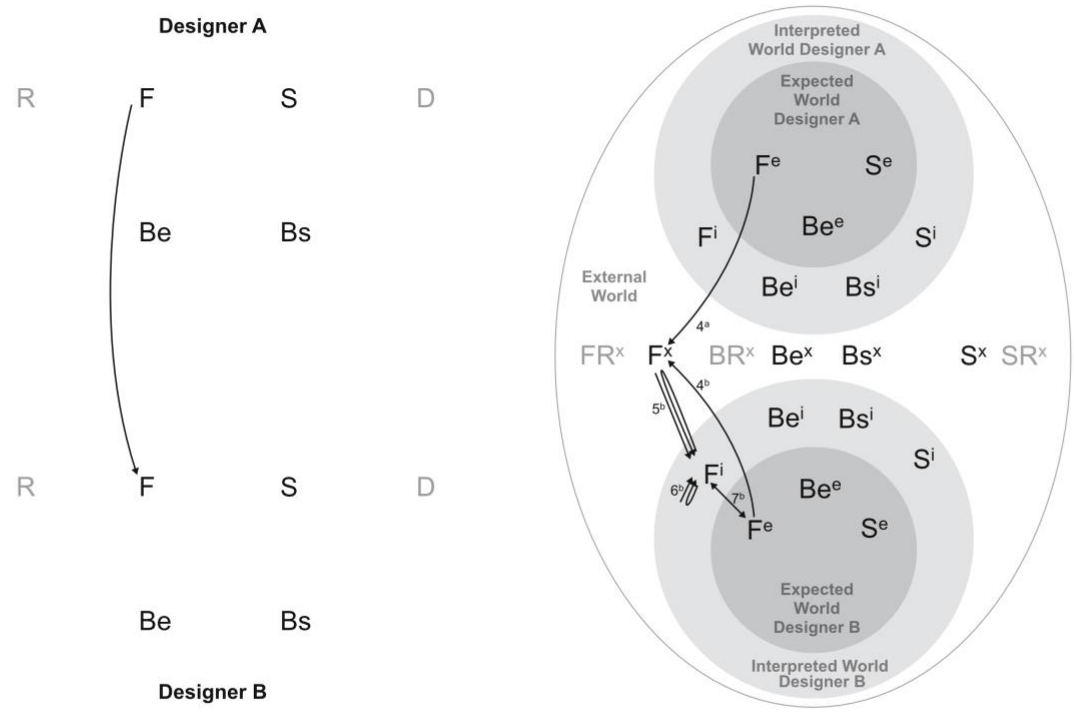
(a) (b)

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

For 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), such as increasing reading conditions. 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), such as connecting the building to nature.



(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). For example, designer A can express concerns about smoothing the transition between the front desk and the reading room. 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 another

Be^x (process 9^b), that can be a counter intention on using ceilings height to highlight the transition between both spaces.

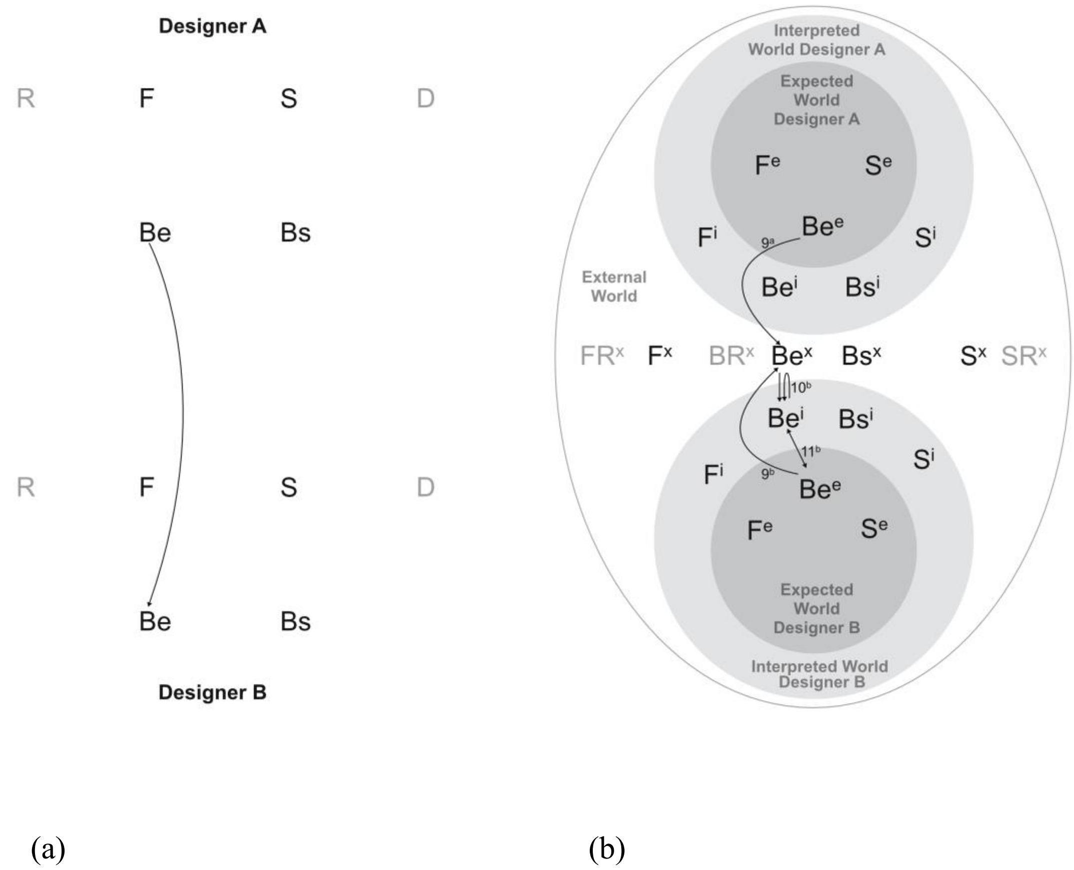
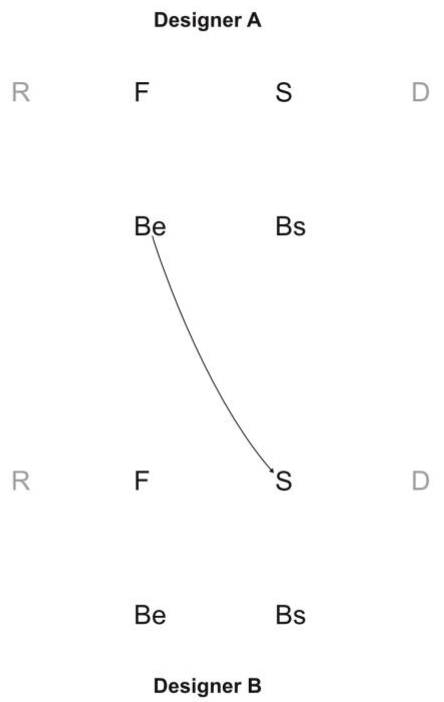


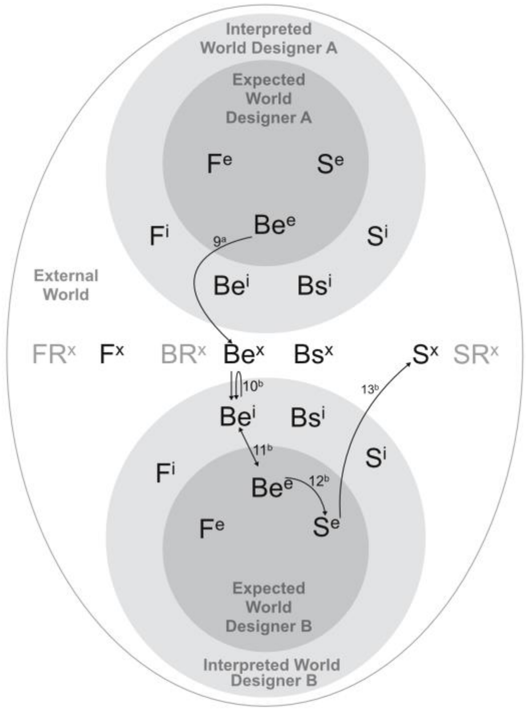
Figure 9. (a) FBS Formulation by the co-construction of Be from Be, (b) situated FBS Formulation by the co-construction of Be from Be

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) questioning how to avoid light glare that dazzles readers. 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) such as a proposition to place conic shaped skylights.



(a)

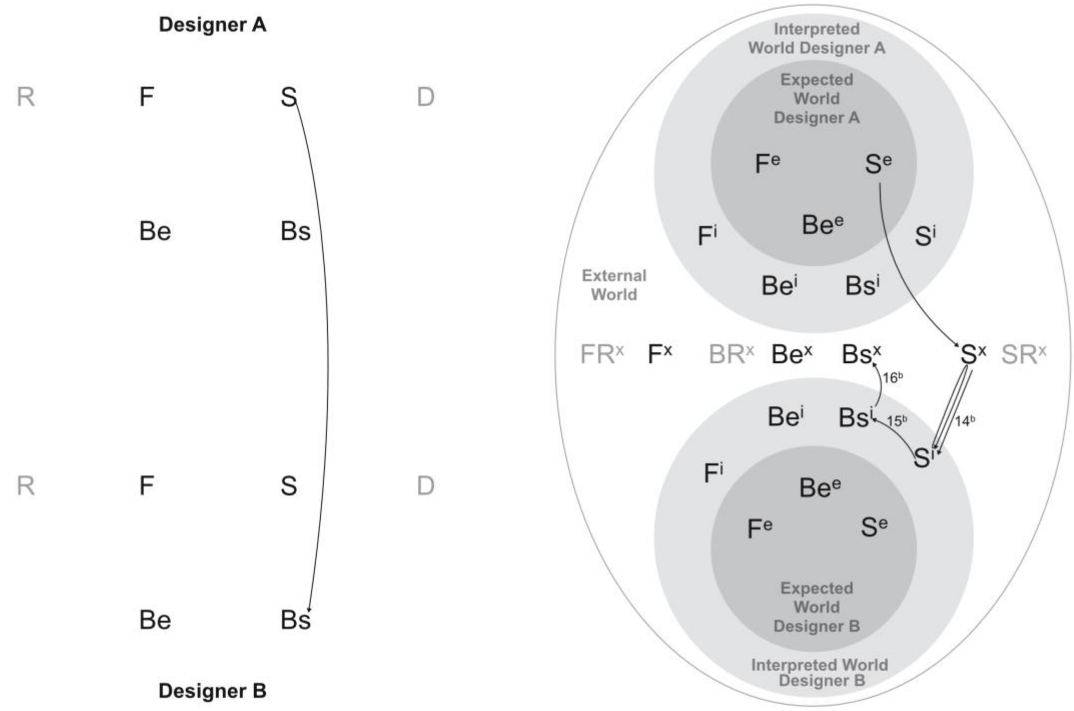


(b)

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 is the 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), for example a wavy ceiling in the reading room, 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 15b). This interpreted behavior (Bs^i) is then externalized by designer B into a behavior from structure (Bs^x) (process 16^b) referring to the quality of that ceiling to reduce noise propagation and echo.



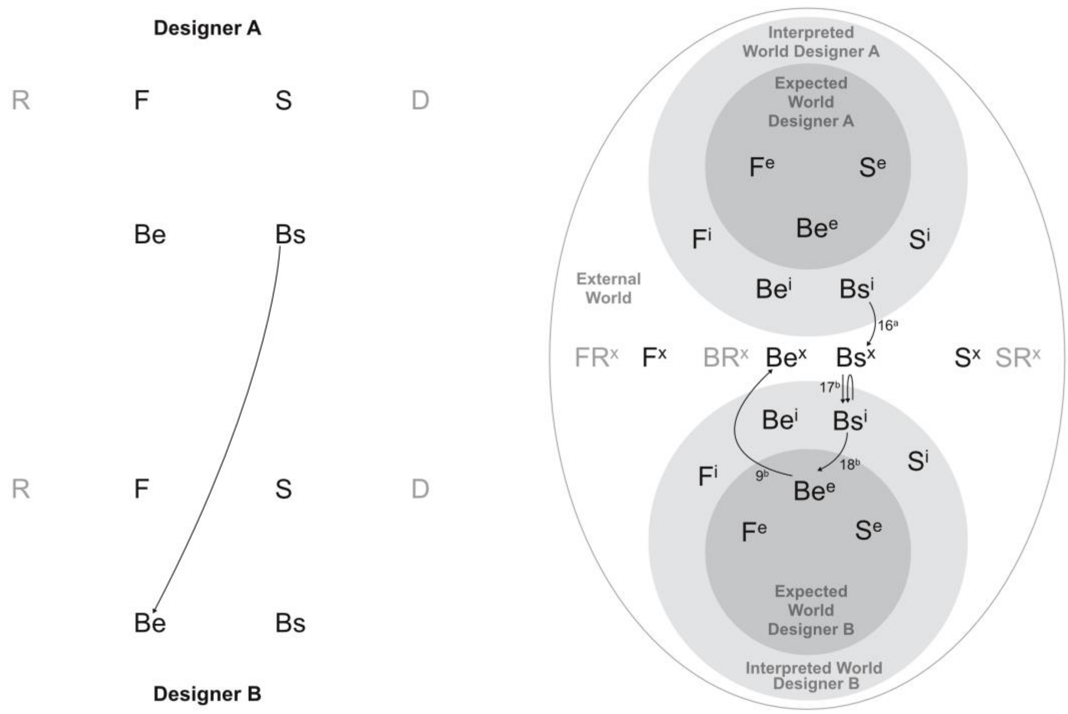
(a) (b)

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

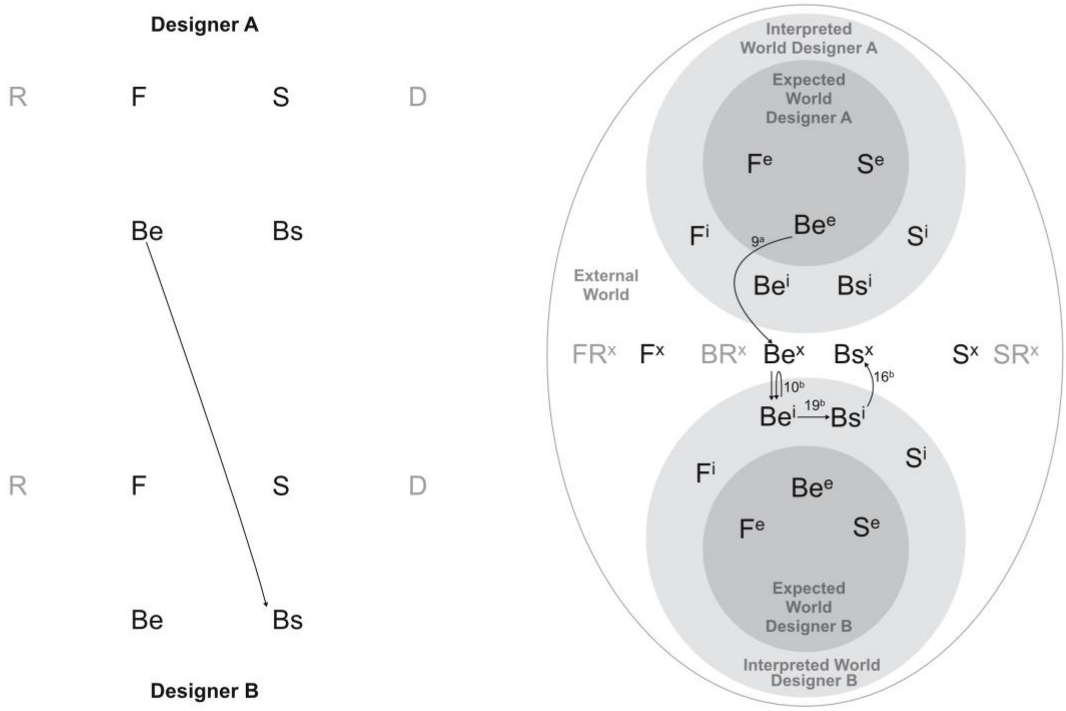
In co-constructed evaluation can be a comparison between an expected behavior (Be) generated by a designer, for example trying to manage noise in the reading room, and a behavior derived from structure (Bs) from another designer, like the quality of the wavy ceiling that reduces noise echoes, Figure 12, or inversely, Figure 13. In the first 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 9a). 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).

In the second 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



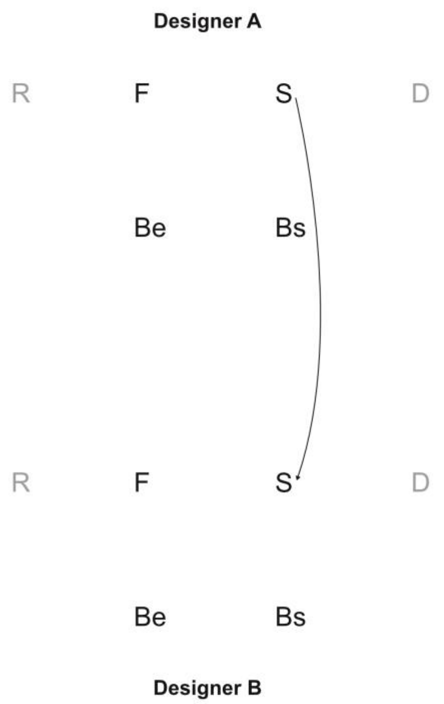
(a) (b)

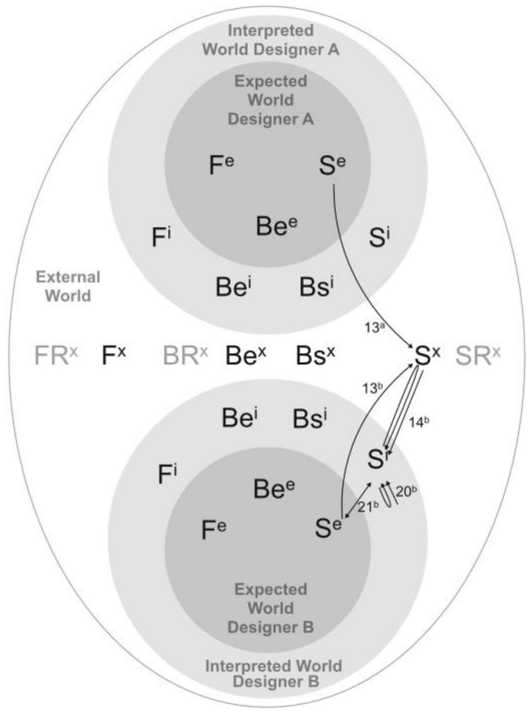
Figure 13. (a) FBS co-evaluation, Be to Bs, (b) situated FBS co-evaluation, Be to Bs

3.8 Reformulation 1: co-construction of structure based on the evaluation of 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^a), for example a description of horizontal windows framed on the landscape horizon. 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 as another structure (S^x) by designer

B (process 13[b]), such as a proposition for a curved skylight monitor instead.



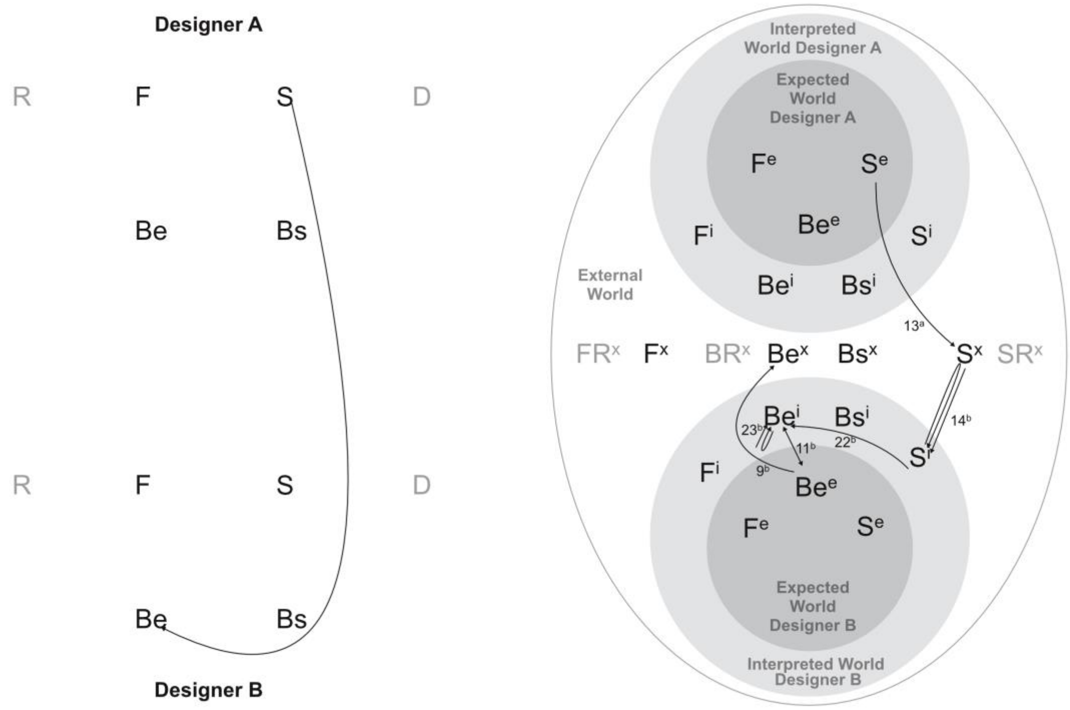


(a) (b)

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 based on the evaluation of 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]), such as the curved conic skylights. 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) is used to reformulate 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). Designer's B proposition can be to adjust the conic aperture to increase daylight in the reading room.

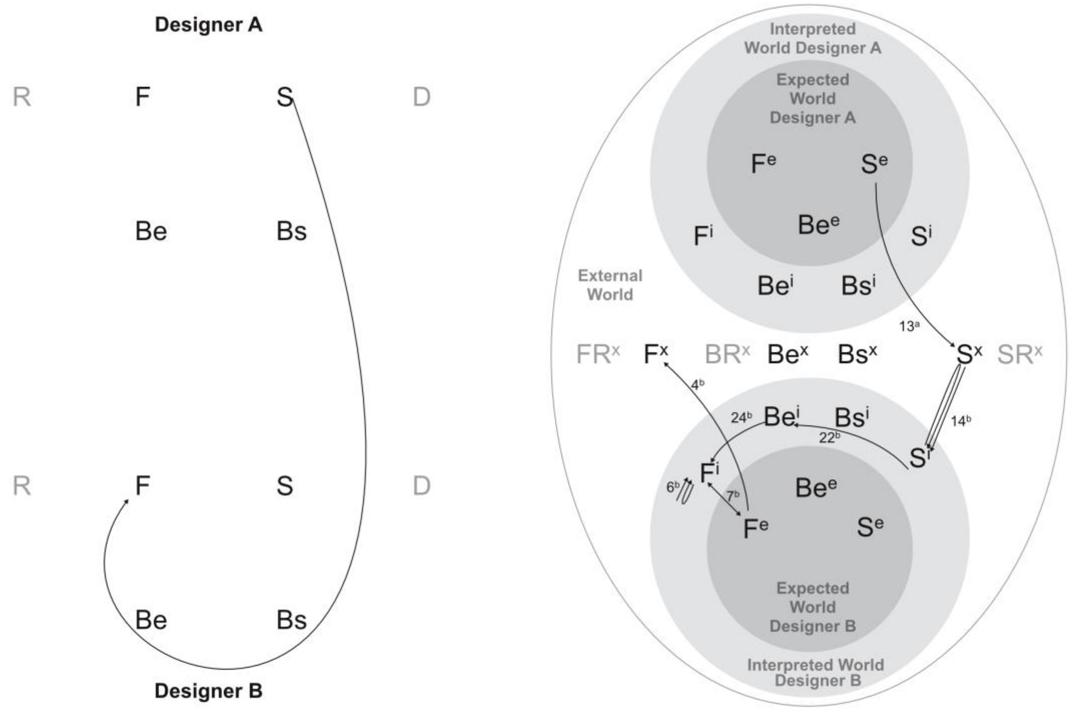


(a) (b)

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 based on the evaluation of 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). As an example, we can take the same design structure of the curved conic skylights. 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, that can suggest that the lighting could also be a part of the natural ventilation system.

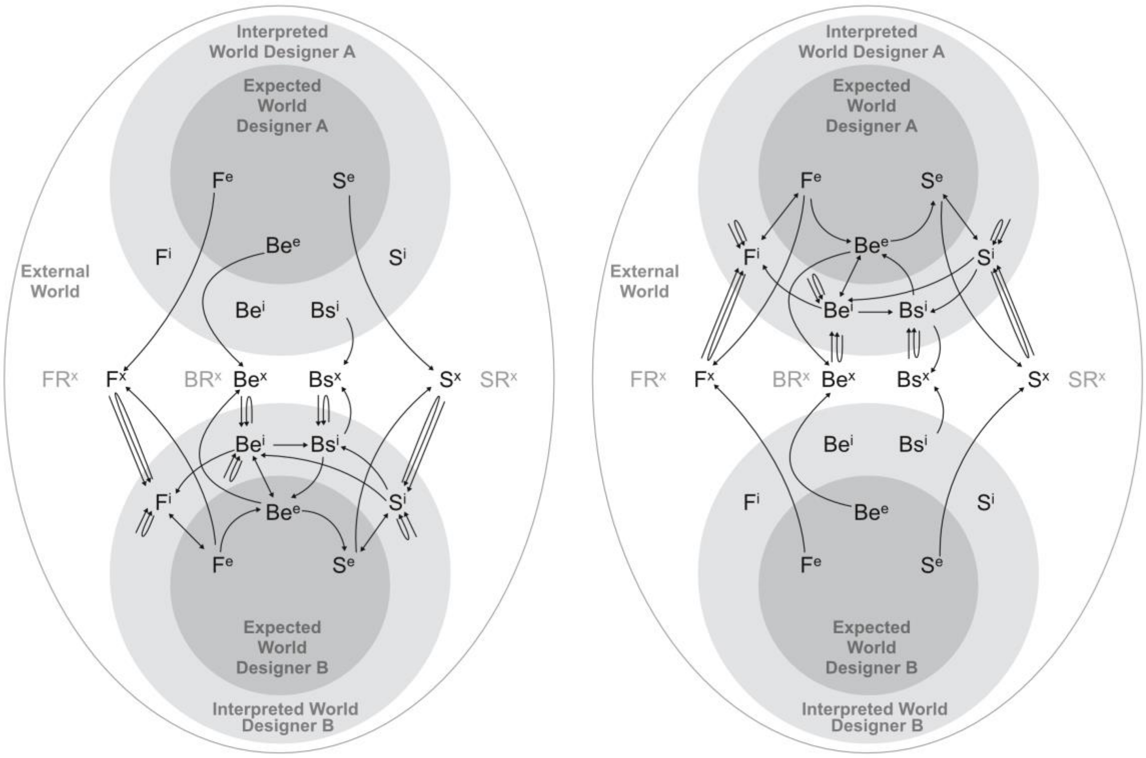


(a) (b)

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, represents 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 situated cognitive design processes in a collaborative setting. This model shows that co-design is not a simple cognitive act.

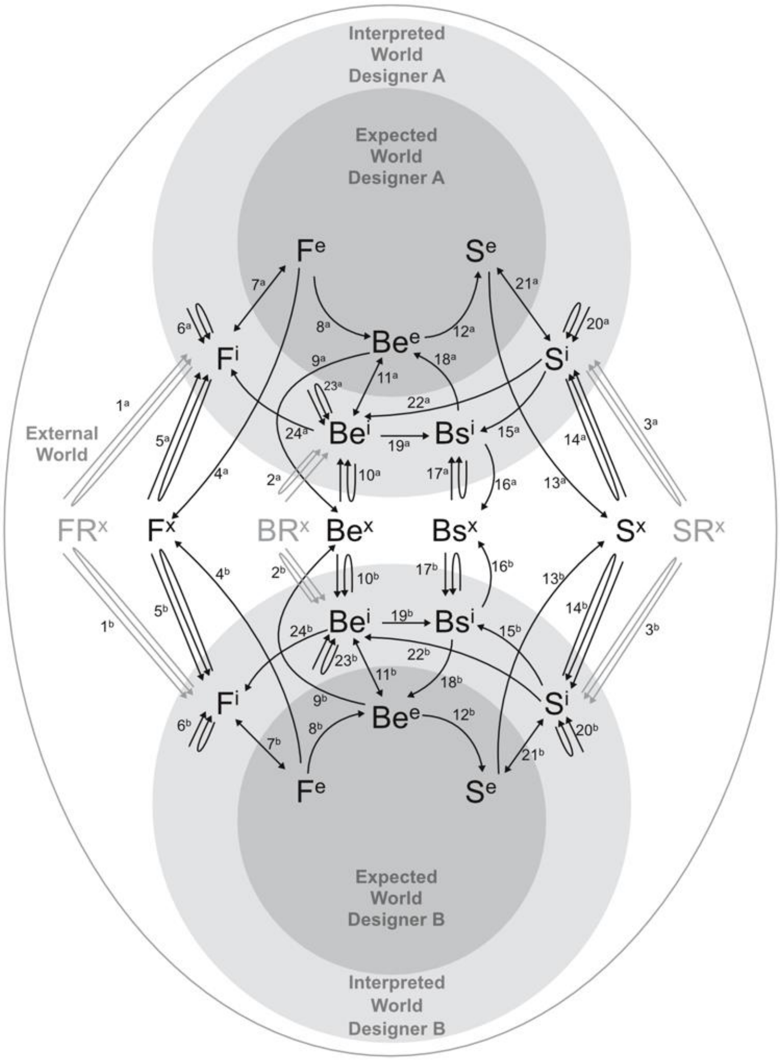


Figure 18. Situated FBS model of co-design processes

3.12 Using the situated FBS co-design model to represent a series of co-design processes: illustrated example

The situated FBS co-design model is commutative, however, due to the situatedness of the design activity, each designer will react differently to what their team members 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 team members through their shared external design representation. To demonstrate how our model functions, we present an example of an excerpt 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 Song, et al, 2016). The session had been previously transcribed and coded using the FBS design issues. 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. Figure 19 shows a development of 6 subsequent sFBS design processes in a collaborative setting, that are either individual or co-constructed. In that excerpt, both designers are discussing solutions to open the window.

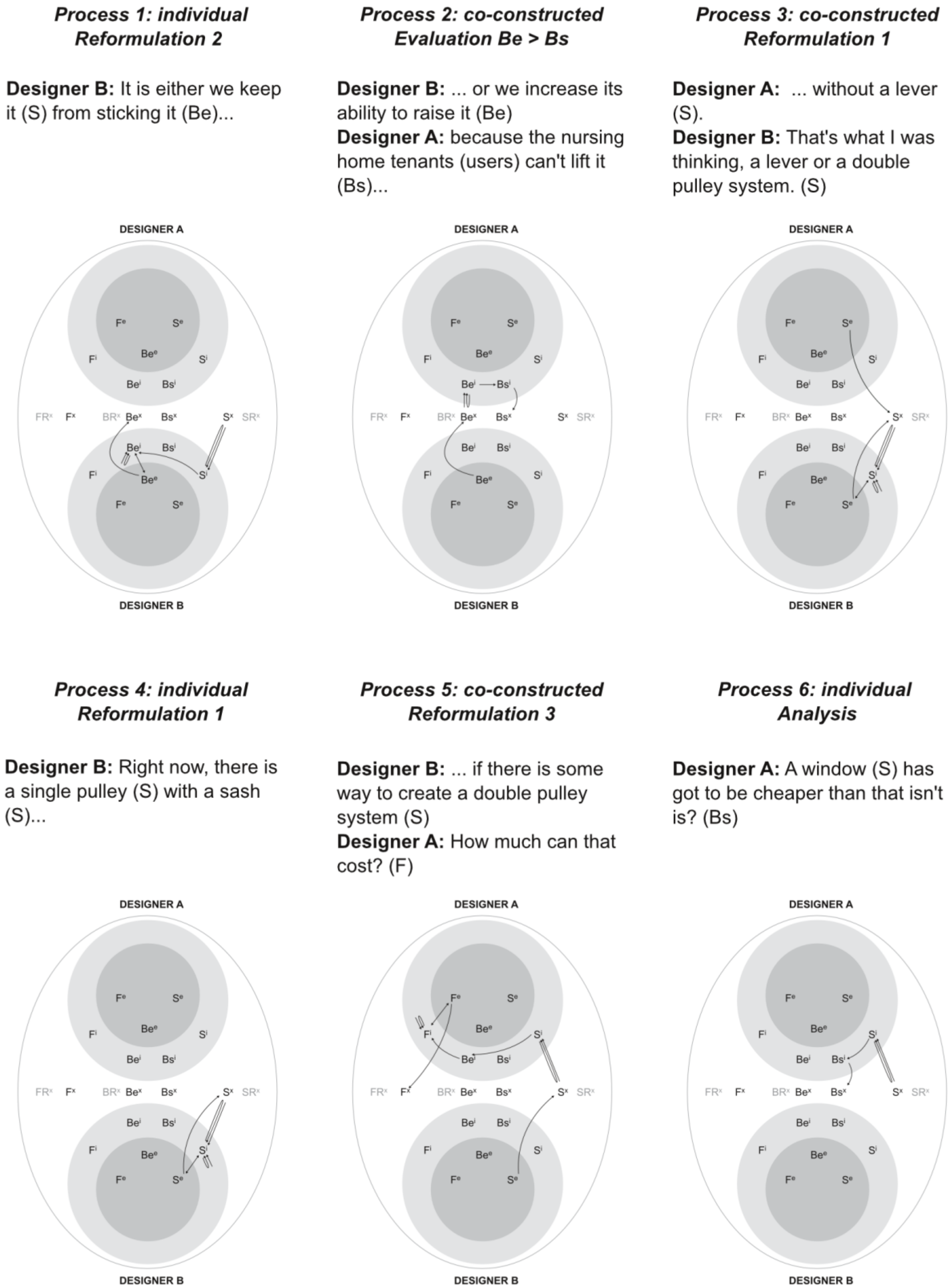


Figure 19. Example of design processes from session excerpt and their representation in the co-design model

4. Discussion

The situated FBS co-design model provides a clear representation of the occurrence of situated cognitive actions during design sessions. A particular significance of our model is its scalability as it can grow to represent more complex co-design situations. Team members communicate through the external world. There is one instance of the design artefact in the external world at any time being focused on, so that increasing the 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, B^x and S^x). Figure 20 presents the situated FBS co-design model for 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 a large number of designers and is able to include teams as systems and subsystems that represent the complex organizations of teams of designers working on the same design.

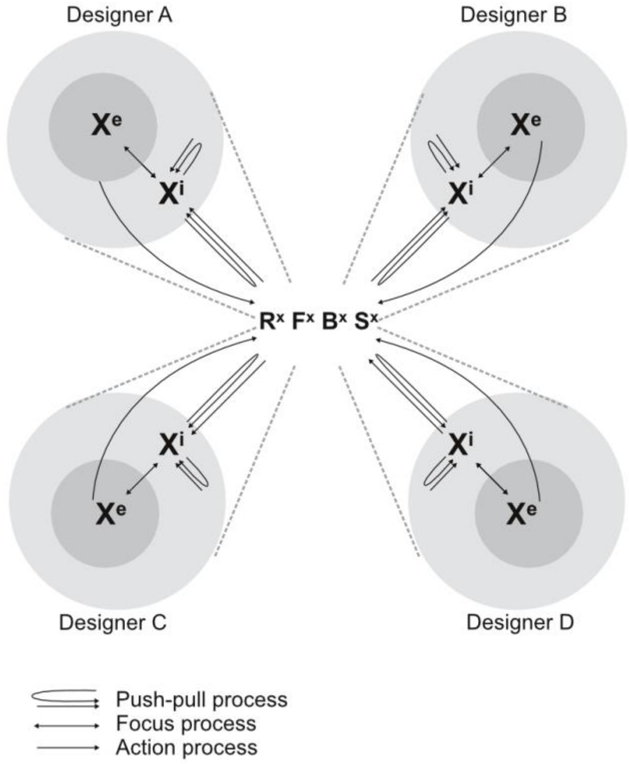


Figure 20. Situated FBS co-design processes for a team of four designers

In Figure 21 we show how the co-design model develops while increasing the number of teams. Here, three teams of different sizes work together with different interactions. All teams co-design on the overall design object represented by the R^x, F^x, B^x, $S^{x\ 1,2,3}$. Teams 2 and 3 also work on a sub-part part of the design object that has another instance (R^{x1}, F^{x1}, B^{x1}, $S^{x1\ 2,3}$) in the external world.

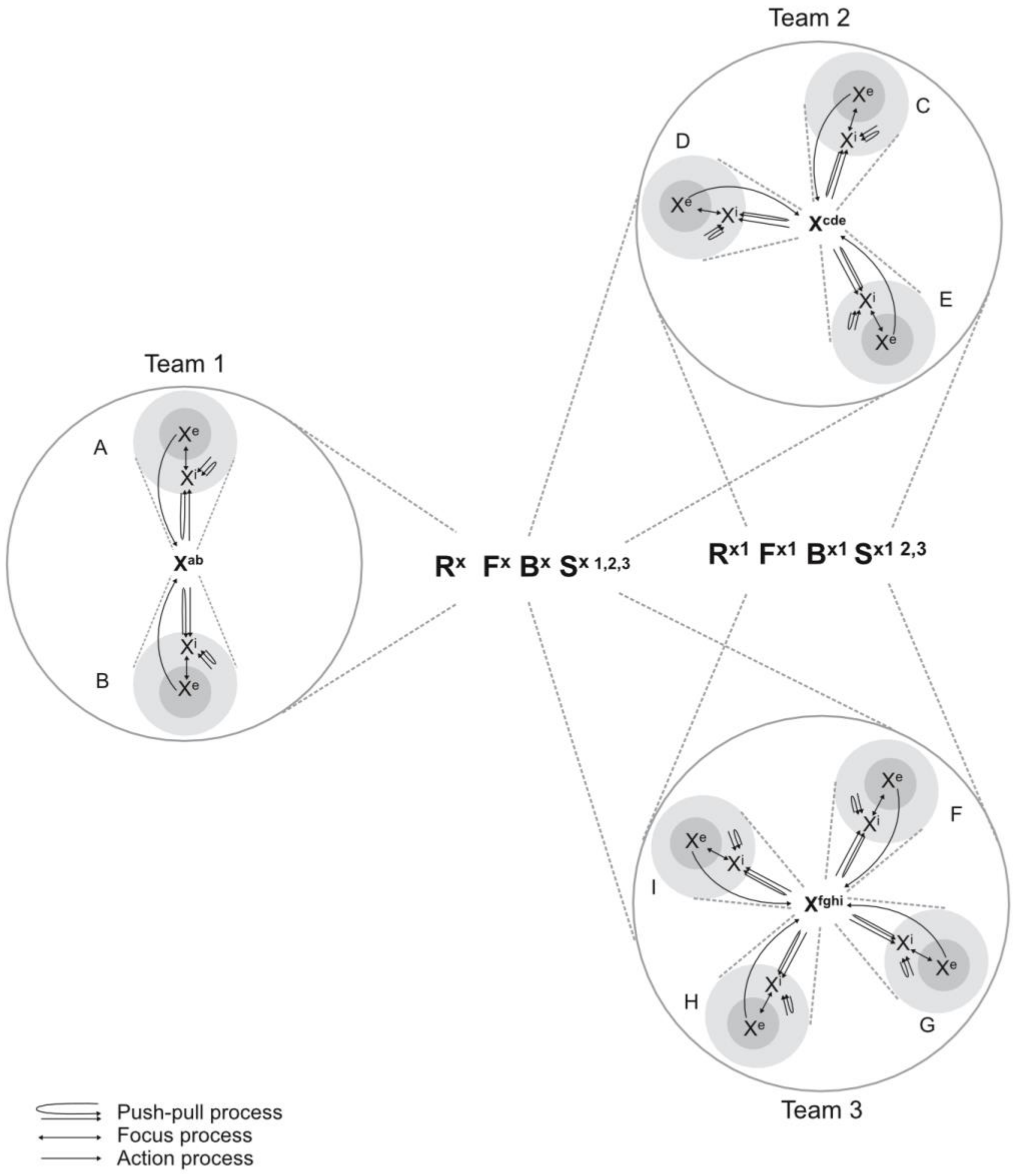


Figure 21. Situated FBS co-design processes for multiple teams each with a varying number of designers, where Team 1 interacts with Teams 2, and 3 while working on the design in the external representation R^x, F^x, B^x, S^x, while Teams 2 and 3 also separately interacts with each other while working on the design component in the external representation R^{x1}, F^{x1}, B^{x1}, S^{x1}.

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. In existing co-design models the situatedness of co-design is not addressed as internal cognitive thinking processes and is 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. 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.

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 model represents designers cognitive processes while co-designing, and is not a mechanistic set of processes to be followed. 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, a possibility to describe designers' cognitive processes and a new perspective to study similarities and differences in co-design situations. The scalability of the model is essential, since co-design can involve multiple team members working on the same design artefact and teams of teams as in systems design. 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.

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