PLM and architectural rehabilitation : a framework to improve collaboration in the early stages of design

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Abstract: Recent evolutions in French law regarding accessibility of public buildings have prompted a rise in the need for methods and tools to rehabilitate such structures in order to make them accessible to disabled users. Architectural rehabilitation is an exceedingly complex design process, in particular because of a legal framework which strongly impacts on the structure of collaboration, and of the need to take into account characteristics of existing buildings. In this paper, we describe a participatory design methodology applied in the rehabilitation of a School of Engineering in France, in order to improve its accessibility, and describe the basic functionalities of a software tool to assist Collaborative Engineering in architectural redesign projects.

Keywords: PLM, building rehabilitation, accessibility, disabled users.

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Introduction

In France, the "February 11th, 2005" Law, named after its date of enactment, stresses the need for *equal rights, opportunities, and participation to citizenship for all disabled persons* (Winance *et al.*, 2007). This law introduced a general principle of accessibility in French society, pertaining to many aspects of public life: sustained employment, urban travel, accessibility of public buildings, etc. Regarding the latter, the Law states that *architectural buildings, structures and equipment located both inside and outside of residential premises, whether public or private property, Establishments of Public Accommodation, locations open to the public and workplaces must be accessible to all and notably to disabled persons whatever the nature of their disability, notably physical, sensory, cognitive, mental, or psychical.*

Despite the fact that the law has prompted much work to rehabilitate public premises, there exist at the time of writing no clear methodology, and few design criteria, to assist rehabilitation of architectural buildings in order to improve their accessibility to the disabled. The key goals of this paper are (Figure 1):

- To define the backbone of a tool to assist the early stages of design, applied to architectural rehabilitation, and its integration with existing tools;
- To describe the two first tool-blocks of our model, using a simple CAD representation and an annotation tool.

We first define architectural rehabilitation as a design process affected by specific, context-related constraints. We then describe difficulties related to integrating data related to users, in particular to disabled users, in this design process, from a Collaborative Engineering (CE) framework. In the third part, we propose that Product Lifecycle Management (PLM) methods and tools may assist CE in architectural rehabilitation. Finally, we describe a software platform under development, aiming to assist CE in a PLM framework, and describe a case study: the rehabilitation of a French School of Engineering. We conclude the paper with some prospects for future research and development of this tool.

1 Architectural rehabilitation as a constrained design process

Design science has a somewhat ambiguous relationship with architectural design, viewing it both as one instance of a *generic* activity and as a *specific* practice, or form of design (Visser, 2009). The first view derives from Simon's view that architecture is a

typical example of a design activity which he classifies as an "ill-structured" problem, *i.e.* one where the problem space's start-state, goal-state, and/or available operators are not known in advance. Designer activity involves gradually defining this problem space. From a project-based view, this implies that as time progresses, designers' freedom to make decisions reduces as the accumulated information about future building specifications increases (Midler, 1995). Furthermore, many authors have argued that this collaborative work is guided by various artifacts, such as sketches or plans, alternately termed intermediary objects, boundary objects, or intermediate representations (Bouchard *et al.*, 2005; Boujut & Blanco, 2003). Such artifacts are a means to generate design alternatives and consensus between the various stakeholders involved. The second view describes architecture as a specific practice, and strives to uncover the architect's specific expertise in the task of designing buildings (Akin, 1986). Without denying the importance of the first strand of research, our work is based on the second approach.

More specifically, we are concerned with tasks of architectural rehabilitation or redesign. These can be viewed as a means to ensure that an existing building continues to generate value to its users for as long as possible instead of engaging in a costly process of demolition and reconstruction (Lindekens *et al.*, 2003). These authors point out such projects take place in an "enlarged context" with a need to take into account the building's history, physical properties, structural characteristics, etc. In other words, architects must manage the constraints that come with the project, in the sense of a partial description of the characteristics of the solution (Stefik, 1981), as well as constraints related to project operation, *e.g.* time or cost limitations.

2   Integrating use-related data in architectural rehabilitation

Although many authors highlight the need to provide architects with data regarding future users and their activities to assist user-centered architectural design, one can point out that the complex planning process involved both in architectural design and redesign, may make this a very complex task. An extensive survey has been carried out describing the sources of this complexity in the French social and legal context of public architectural contracting (Martin, 1998). The prime cause of these issues derives from a legal framework defining two separate actors: the *client*, *i.e.* the entity for whom the architectural project is being undertaken, and the *contractor i.e.* the entity in charge of carrying out design and supervising construction work, for example the architect, structural engineer, etc. Communication between the two is ensured by production of an intermediary object termed the "architectural program", broadly defining the intended characteristics of the building from the client's point of view. A key issue when striving to integrate user-related data is therefore separation between design and decision-making, the former based on academic training and work experience, the latter occupying a high position in decisional terms, but usually with little or no training nor experience in design projects.

To counter these issues, Martin (*op.cit.*) proposes a model of user-centered architectural design (Figure 2) based on the following principles: 1) a clear identification of the actual stakeholders behind the "client" entity and focus of design on the analysis of situations deemed characteristic of future building use (Daniellou, 2007); 2) a good knowledge of

the contractor's data requirements for redesign: when and in what form should they be provided? 3) a strict adherence to participatory design principles, *i.e.* direct involvement of users in the design process; and 4) providing means for continuous client-contractor interactions throughout the project.

These principles hold true in the case of architectural redesign, but are all the more important that such projects are associated with more stringent constraints. Time and cost constraints (Savage et al., 1998) are usually more intense, since design and construction need to be balanced against the requirements of continued building operation. Consequently, redesign projects often last several years and are often spread out over a series of minor alterations rather than one major "makeover". However, these principles only provide a general framework for user-centered architectural redesign, whereas redesigning buildings to be accessible to disabled persons poses specific issues. To present our approach, which focuses on accessibility of buildings to the disabled, we first need to clarify the interrelations between the concepts of disability, accessibility, and user-centered design.

The definition of disability has undergone major evolutions in recent years, mirroring evolutions in its recognition by the welfare system. The previously dominant, medical approach of disability, based on its definition as a physical abnormality, has gradually been displaced by a social-centric view where disability is produced by the interaction of individual limitations with environmental determinants, hindering participation to social life (Fougeyrollas, 1995). The definition chosen by the World Health Organization (WHO) bridges these two views by distinguishing three related concepts (Mitra, 2006): *impairment* refers to a problem in body function or structure; *activity limitation*, to a difficulty encountered by an individual in executing a task or action; and *participation restriction,* to a problem experienced by an individual in involvement in life situations. Disability refers to all three levels of this continuum. Several scholars, however, have criticized the WHO definition as being overly materialistic (Burchardt, 2004; Mitra, 2006; Terzi, 2004). Instead, they propose an approach based on the concepts of capabilities (Sen, 1999) and focused on providing users with opportunities for personal development. Sen's framework distinguishes two key concepts: *functioning*, i.e. the activities a person carries out, and *capabilities*, i.e. the practical opportunities available to the individual to achieve a given functioning. In this framework disability can be understood as deprivation of capability set as a result of an impairment, with variable on impact on the functioning level. Disability, therefore, arises from several factors: the impairment, the resources available to the individual, and the environment (Mitra, 2006). Accessibility, therefore, is a means to provide users of a building with opportunities to carry out activities within this building. These activities are supported by a number of structures within the building (Nelson *et al.*, 2009; Winner, 1986), some of them explicitly– *e.g.* a lecture hall is build to house lessons– and some less so – *e.g.* "gathering areas" may be dotted all around the building.

User-centered design of public buildings thus rests on taking into account characteristics of user activity within the building in order to identify means to efficiently restore their capabilities for action. Theories of human activity have evolved in recent years, generally highlighting their situated nature (Béguin & Clot, 2004; Suchman, 2007). As Suchman writes "*every course of action depends in essential ways upon its material and social circumstances*". To structure their understanding of this enormous variability, designers frequently rely on specific devices.

At the micro level, scenarios are used as narrative descriptions of specific situations of use to ensure user-centeredness in the design process and "make claims" (Carroll & Rosson, 1992) regarding the relationships between 1) building characteristics and limitations of user capabilities, and 2) restoration of these capabilities through alterations in the building design.

At the macro level, design decisions can be evaluated based on iterative simulations of user behavior. Although the traditional approach of iterative prototyping and user testing is mostly impractical in architectural design, it is certainly a viable tool for redesign: designers are then led to construct and evaluate situations representative of future use by browsing "situation libraries" (Daniellou, 2007).

In both cases, the designer is still dependent upon single situations as a unit of analysis. To us, a major consequence of this is that User Centered Design fails to take into account the dual complexity of the building's lifecycle: on the one hand, environmental characteristics are liable to restrict users' capabilities regarding some aspects of building use, *e.g.* when isolating certain areas of the building for maintenance; on the other, constraints surrounding architectural redesign (see above) cast some uncertainty as to how long such limitations are to last. For both these reasons, we posit that implementing a Product Lifecycle Management tool might provide useful assistance to architectural redesign.

3 Product lifecycle management as a tool for collaborative engineering in architectural redesign

Product Lifecycle Management (PLM) is a design framework aiming to cover all the stages of a product's development through integration of all processes and actors involved in the project (Saaksvuori & Immonen, 2008). Its main focus is on the design of industrial products: Sharma's (2005) integrated PLM framework views collaboration in product development as "*based on common collaborative processes and goals, connecting people, process and data in such an arrangement*". The process itself has several stages: product concept, design, prototype, plan, develop, manufacture, market, sell, service and recycle. Over the last several years, PLM has emerged as a business approach for the creation, management, and use of product-related intellectual capital and information throughout the lifecycle. PLM is therefore a paradigm where processes are as important, if not more so, than data.

3.1 PLM and architectural projects

PLM is widely studied when dealing with mechanical or engineering products. But, if one wants to represent the entire lifecycle of a building, and store intermediate representations (IRs) or data about this artifact, fewer solutions are available. Indeed, the data (naming, versioning…) used in engineering products relate to a product whereas the data used in architectural design related to a building which can suddenly evolve without foreseeable reason (explosion, reorganization etc…). So the level of detail of the studied models is different, even if lightweight representations can be used in both cases. In our work, we focus on the "portion level", as portion is a subset of an artifact (Dudek &

Blaise, 2008). However, computer science developments for buildings are nowadays possible as many conceptual modeling languages supporting time extension have been developed. For example, the ERT modeling language (Entity Relationship with Time) presented by McBrien and his colleagues (1992) allows *time-stamping* entities and relationships. During the construction and the evolution of a building (or artifact), a spatiotemporal information system (STIS) is created. Integrating temporal evolutions of behaviour is one of the most important issues of STIS engineering (Renolen, 1997).

In architectural projects, when dealing with public buildings, a collaborative engineering tool should provide designers with temporally-ordered IRs (Bouchard et al., 2005) of the edifice. It should also store design recommendations and design alternatives, so that each stakeholder might be able to understand the building lifecycle. To achieve this, "history graphs" (Renolen, 1996) describe an artifact's history through a series of consecutive versions and transitions, characterized by a time interval. Transitions are drawn using boxes with circular ends and versions are drawn with a square rectangle. Moreover, some methodological frameworks of description of architectural changes have been developed, especially for heritage architecture. For example, Dudek and Blaise (2008) make a strong differentiation between the evolution of an artefact and its lifecycles. Thus, the evolution of an artefact is "*the time slot between its creation and its extinction*". An artefact's lifecycle identifies a "*time slot corresponding to a consistent physical continuum, during which transformations are partial*". So, the evolution of an artefact (*e.g.* a School of Engineering) may contain several lifecycles, which is not common for an engineering product. For example, in case of the rehabilitation of a School of Engineering (see section 4), the alterations made to improve the accessibility of a lecture hall (Figure 5) relate to this *lifecycle* feature. On the other hand, rebuilding the whole workshop area is an *evolution*, and implies a new lifecycle for this particular feature. Each lifecycle of the studied edifice thus designates a sum of states, with no major transformation; and transitions, during which transformation is in progress. Dudek & Blaise (2008) propose "*diagrams that act as visual explanations of the artefact's lifecycle*". The tool we present in section 4.2 is implemented with diachrograms that present the evolution of the artefact along a time axis (Figure 7). The promise behind PLM, as it relates to the problems we outline in architectural redesign, thus lies in seamless integration of "*all* the information produced throughout *all* phases of a product's life cycle to *everyone* in an organization, along with key suppliers and customers" (Sudarsan *et al.*, 2008).

Our approach is further motivated by two points: first, in spite of the fact that product design and architectural design refer to very different practices, recent work has attempted to apply models, methods and tools of industrial design to address unmet needs of architects. Second, major rehabilitation projects lasting several years involve handling large numbers of IRs and accessing information generated at any time during the building's lifespan, which typically lasts decades or even centuries.

Following this view, we defend Martin's (1998) view that Client/Contractor interactions in architectural redesign need to be better organized. However, ergonomist involvement is not sufficient to ensure user-centeredness of the redesign process: one must also ensure that the relevant data and representations are available to stakeholders at the right time. Ding *et al.* (2009) stress that multiple viewpoints in the design process cause increased processing times and storage needs, and that annotated lightweight representations are

needed to facilitate communication and storage of project-related data. Using such representations, a Client or Contractor might at any time extract information regarding ongoing and upcoming projects and events involving the building, to better plan design and construction work, and to make decisions mindful of multiple points of view. In particular, annotation offers the possibility to explicitly state and debate (*e.g.* in a participatory design team) possible alterations to the environments and their expected effects on user activity and capabilities. Geryville *et al.* (2006) also point out that multidisciplinary collaboration allows stakeholders to express their interests as regards future user activity, using a variety of conditions and/or representations, and to follow various processes to deploy and extract those representations. The aim of PLM as a tool for CE in architectural design is to provide, *e.g.* in the rehabilitation of public buildings, these representations and to facilitate their extraction. Such representations must also be congruent with architectural design practice. For this reason, we posit that a PLM tool for architectural design should strongly take into account the main type of Product Data Management tool used in this field, namely Building Information Modeling (BIM) tools.

3.2 PLM and Building Information Modeling

Although much work has focused on 3D representations, several authors (Grilo & Jardim-Goncalves, in press) have shown that despite the existence and widespread use of 3D CAD software in architectural design and redesign, the dominant format for collaborative work and communication in the early stages of the process is 2D-based; depending on the stage of work involved, design decisions may be embodied in sketches, floor plans in various levels of detail, etc. 3D representations are used more intermittently, to illustrate design decisions in conjunction with 2D models and other documents. The recognition of the need to provide stakeholders with richer information in the redesign process is the main rationale behind Building Information Modeling (BIM), which uses object-oriented programming to facilitate interoperability between the design and construction stages (Eastman *et al.*, 2003). The first report of the potential of BIM to transform processes in the architecture, engineering and construction (AEC) industry emerged in the late 1980s and early 1990s (Linderoth, 2010). Furthermore, Manning and Messner (2008) have noted several benefits of using BIM in the conceptual stage of design, e.g. rapid visualization and improved decision support in the project development process. However, with respect to section 2, several points must be made:

– BIM software clearly complements the PLM framework, but focuses mainly on bridging the information gap between design and product validation before construction (see Figure 3), not on the user-centered design of buildings, although recent work has begun to address this concern (van Nederveen & Gielingh, 2008);
– Some BIM standards have been developed. For example, the National BIM standard approach, well suited to the construction of new buildings, uses groups of experts in AEC to specify use-cases in what they call "Information Delivery Manuals" (IDMs). These IDMs serve as a basis to create specifics import and export translators to facilitate collaboration between design and construction stakeholders (Eastman *et al.*, 2010);
– Assisting the redesign of existing buildings, especially to the degree befalling France at time of writing, is less of a concern to BIM than assisting the design of new buildings allowing leeway for redesign later in the lifecycle;

– More importantly to us, BIM software is currently incompatible with design approaches placing user involvement at their core such as participatory design, and is therefore of limited interest to user-centered architectural redesign.

Since BIM, nowadays, helps manage efficiently collaborative information exchange in building design and construction, the position of our work is to define a global framework to assist stakeholders in the early stages of design towards efficient architectural rehabilitation, taking into account issues of accessibility. This framework has been developed through a methodology that aimed to develop a tool for designers. As we point out below, a tool for CE in architectural design should be a synthesis between existing methodologies and user-centered approaches, from the early stages of design. We now present the results obtained by using this tool, and define its structure and functionalities.

4   Results

4.1 A model of the early stages of architectural redesign

Segonds et al. (2009) have compared several models of the engineering design process to propose a descriptive framework of the "early stages" of design, as well as a model for collaborative work in this stage. This model, although based on models of product design, lends itself well to the early stages of architectural design (Figure 3).

This model is aimed to help the Client to debate design alternatives of the overall building rehabilitation with the different stakeholders, and especially the Contractor. It is strongly influenced by the work of Aoussat *et al* (2000) in the following respects:

– Emphasis on the multidisciplinary nature of design work: each stage involves professionals from various fields who should be able to "plug in" to the system to access relevant information to the tasks performed by them in any given stage;

– Redesign work, ranging from the reception, of the program by the architect, to the elaboration of floor plans, comprises four stages:
  o Translation and interpretation of client needs: these are embodied in the program. The client may rely on an ergonomist at this stage to ensure user-centeredness throughout the redesign process. The principles of his/her intervention are those outlined in section 2. Observation of current building use aims to identify accessibility issues, which are not necessarily restricted to disabled users. Observation results are reported in annotations made on lightweight 3D representations of locations within the building (Figure 5). This allows designers to gain a clear picture of the ways in which current building characteristics restrict user capabilities for action;
  o Concept search: this is carried out by the architectural firms as a response to the program defined by the client. The client must then evaluate concepts presented to him by a number of design firms in order to choose the most viable one. Here, similar IRs allow the client to walk through various usability issues when carrying out this evaluation to choose the most user-friendly redesign concept.

o Design then relies on producing a number of deliverables describing the redesigned building in increasing detail. Likewise, the focus on accessibility issues will be more specific. For example, whereas concept search may strive in finding ways for wheelchair-bound users to access the main structures of the building, later stages might focus on the specific dimensions of the corridors spanning the paths defined in this way;

o Product validation: this is a more complex issue than in the case of product design, where iterative prototyping and evaluation are commonplace. Validation can take place using "floor plan" IRs or scale models for designers and end users to walk through.

During the two latter steps, most of the data can be managed using BIM software. Our framework aims to extract IRs from this data to implement as the backbone of our tool. The rationale behind a tool to assist User-Centered Design (UCD) stems from the knowledge that integration of user-related data in the redesign process is a complex issue (see section 2) and that this state of affairs is a potent obstacle for contractors and client to access key user-centric data and formulate a specific plan to manage the constraints of redesign and construction. For these reasons, UCD applied to architectural rehabilitation has to be structured using a dedicated tool.

4.2 A tool to structure user-centered design in these early stages

The project upon which this case study is based involves the redesign of a School of Engineering in Paris to ensure compliance to the Disability Law mentioned in introduction within the legal deadline (5 years following the inception of the law).

The School has a diverse population of everyday users numbering approximately as follows: 1,400 students and 200 teaching and administrative staff.

Ergonomics involvement was requested in the needs translation stage of the redesign process. It was based on the model presented in the section above. Its main points were as follows:

- Initial interactions with the client (head of the School board) and with user advocates allowed the ergonomist to gain an overall picture of the activities performed within the school, pertaining to all of its missions: teaching, research, and industrial work. Interviews with these stakeholders focused on activities which were *characteristic*, both of the nominal functioning of the school (e.g. "Tell me about your typical day at the school") and of incidental, *i.e.* rare, situations (e.g. "Can you tell me about any major events, either in the recent past or in the near future, where accessibility was or might be an issue ?").

- These activities were translated to sets of possible access paths using a method similar to the cognitive walkthrough method (Lewis *et al.*, 1990). This allowed the design team to identify a list of relevant locations within the school for finer examination: schoolrooms, restaurant, etc.

- Capability limitations are then imported within a matrix (Figure 4) whose columns correspond to various types of impairment retained for examination in the scope of the design project (motor, visual, and hearing impairments) and whose rows refer to

key tasks defined jointly by the client and users involved in the process, highlighting key priorities for functioning:

- o Entering / exiting the area;

- o Acting within the area, *i.e.* carrying out the tasks for which the area is intended (*e.g.* attending a course, having a meal, etc.)

- o Evacuating the area, i.e. being able to access an exit path under degraded conditions.

Debate in a participatory design team helped us prioritize redesign work to restore user capabilities.

- Needs translation and interpretation relies on simple CAD models using Sketchup to illustrate before/after states of the building and their expected effect on accessibility, for the different disabilities highlighted in the matrix;

These CAD models will be implemented in a Collaborative Engineering tool, and all the stakeholders of the architectural redesign project will be able to access and comment on the decisions take. In the next section we present the overall user interface of the software redesign tool, and its main functionalities.

4.3 Development of a tool to assist collaboration in early design stages

We believe the complexity of the architectural redesign process justifies the need for a new tool to manage the building lifecycle, albeit with a stronger focus on UCD than existing (BIM) software. Our tool is specifically geared to assist cognitive synchronization, assessment of solutions, and proposing solutions (Détienne *et al.*, 2004) in the early stages of architectural rehabilitation. Thanks to this software, various stakeholders will be able to access building-related information stored in a database. This tool prototype rests first and foremost on capitalizing the data generated by the design team in the early stages of redesign, including (but not limited to) data pertaining to user-centered aspects of design. Following the model of early stages of design presented in Figure 3, each stakeholder might "plug in" to the software to contribute and to consult data relevant to his own design expertise and project duties. In particular, design alternatives could be reviewed based on the exchange of multiple annotated IRs (Figure 6).

Figure 7 describes a screen mockup from this proposed software suite.

The headband allows users to log in to four modules that can be plugged from the early stages of rehabilitation. The "Needs" thumbnail (leading to Figure 5) allows the client to specify current functioning limitations for users due to building characteristics, thanks to 3D CAD models, and an annotation tool to highlight accessibility issues. The "Concepts" thumbnail (leading to Figure 6) allows Contractor(s) to propose different solutions to an

accessibility limitation, to import CAD-generated redesign alternatives and broadcast documents to the design team that are relevant to their own expertise. Firms of architects can propose concepts in response to this extended program, which the Client will choose from. If necessary, designers can highlight specific technical solutions with a bubble interface to explain the suggested alterations. Naturally, confidentiality of these contributions will have to be maintained between firms to ensure fairness in the contractor selection process. For example, Figure 7 shows the main entrance of the building which is inaccessible to some users because of stairs. The first concept developed by the architect is an approach ramp, and the second one is an elevator. Choosing between these two (or, indeed, rejecting them both) is partly the client's task. But it may also involve other professional to examine the feasibility of this concept with respect to redesign constraints (*e.g.*, "Are we allowed to encroach onto the street?"). The "Design" and "Validation" thumbnails will allow the Client to follow the project, thanks to IRs sent by the architect and/or the constructor as work progresses. Moreover, these IRs can be presented to future users, who would be able to comment on the evolving solutions as part of participatory design, starting from the early stages of architectural rehabilitation. From there, a collaborative area will allow, with restricted access, stakeholders to check out the evolution of the building. A temporal cursor, located on the top right allows the user to access temporal evolutions of the global building, and of each important feature thanks to the history graph notation (Renolen, 1996). All concepts are stored into a database, and are available throughout the whole of the collaborative work.

Then, the four buttons on the bottom right allow stakeholders and designers:

- To view the current solution under consideration, *i.e.* the latest CAD file, pictures, or historical reconstructions available at any given time and in any given thumbnail/stage of the process (Needs, Concepts, Design or Validation).

- To send IRs of the building to the whole team, via the internet. This function allows speedier collaboration and is useful when a consensus or design decision is urgently needed.

- To add concepts, if the architect has further solutions (or refinements of existing solutions) to propose to the Client.

- To access BIM modules relative to the solution under scrutiny. As seen in section 3.2, this software suite must be linked to BIM software if the concept is sufficiently developed. In the example, as the concept for the main entrance of the building hasn't been chosen so far, the BIM is not developed and the text is in grey italic characters.

This global framework to help optimize Client/Contractor/User collaboration in the early stages of architectural rehabilitation can take into account the global evolution of the building. Annotated lightweight representations of the building allow various stakeholders to collaborate in order to define the most relevant solution to improve accessibility of a public building to its users.

5   Conclusions and future work

In this paper, we have highlighted the sources of complexity for user-centered redesign in a PLM context to assist the architectural rehabilitation of public buildings. To us, the need for an increased focus on collaborative work using PLM in user-centered architectural redesign stems from 1) a social and legal context specific to France, where demands for the rehabilitation of public buildings are liable to become very numerous in the near future; 2) a specific social framework making integration of user-related data and participatory design notoriously difficult; and 3) an inability of design collectives to tackle accessibility issues in a structured fashion. We have proposed the design of a prototype software platform to assist collaborative design in such a context. Our future work will focus on clearer characterization of designer needs and practices in architectural redesign, and on evaluating the successive design iterations of this software suite.

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Figure 1- Framework of the early stages of design process, from (Segonds *et al.*, 2009)
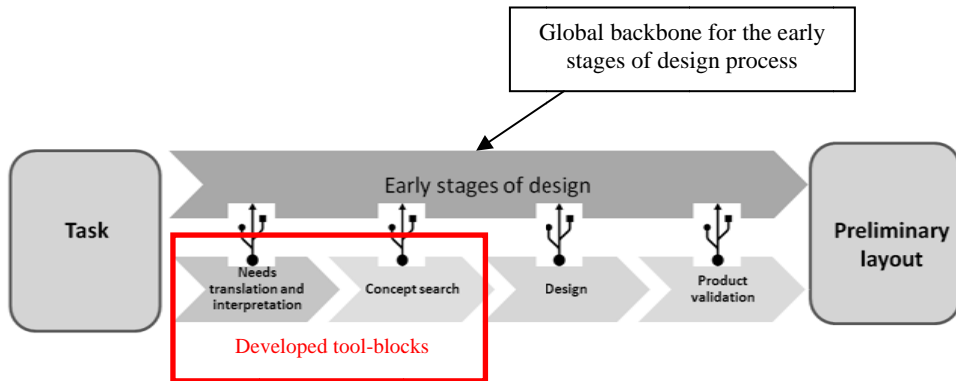
Figure 2 - Model of client-contractor interactions in architectural design (from Martin, 1998)
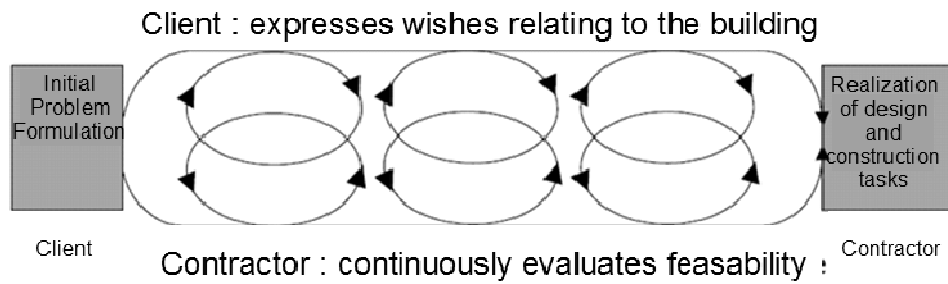
Figure 3 - Model of the early stages of design, position of our work and BIM integration, adapted from (Segonds et al., 2009).
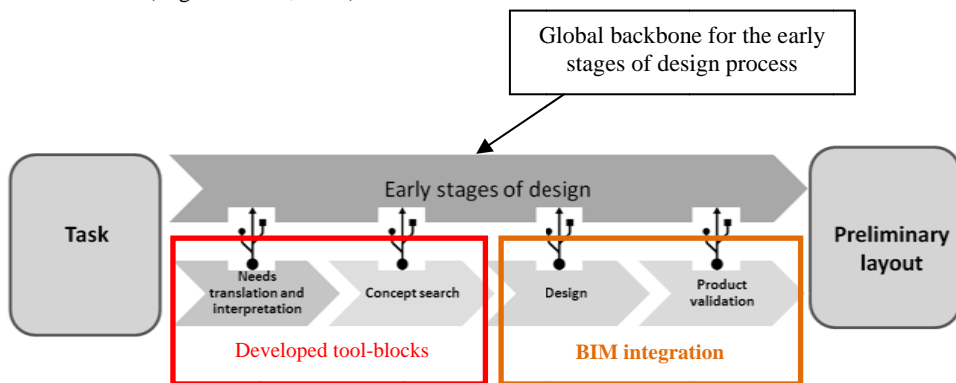
Figure 4 - Capability matrix for the use of one lecture hall. Double-crossed pictures indicate serious capability limitations, single-crossed picture less serious limitations, and no-crossed picture, the relative absence of limitations.

Figure 5 - Capability limitations and underlying causes in a lecture hall
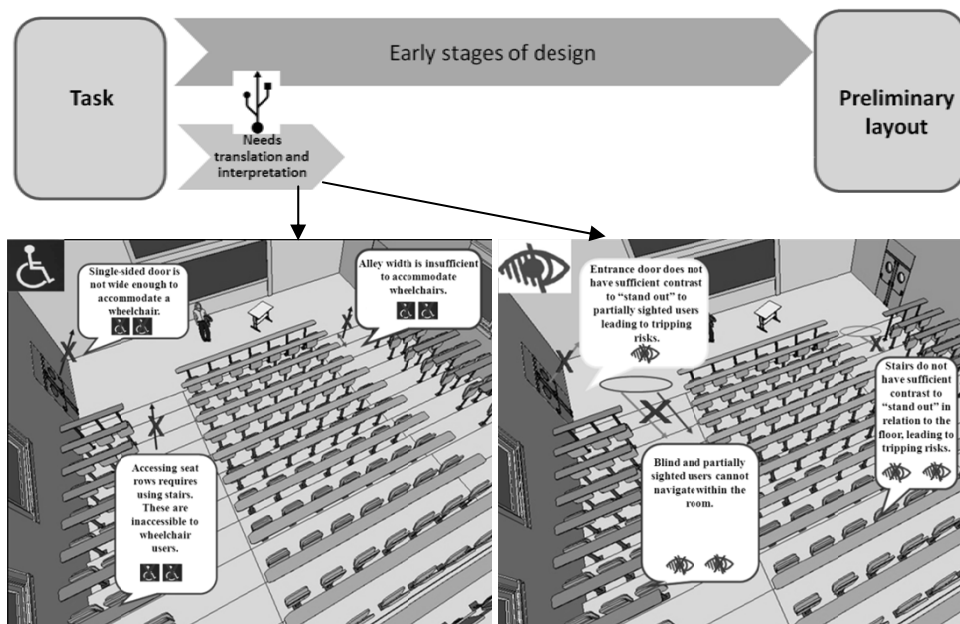
Figure 6 – Putative redesign concepts to restore capabilities in users with motor (left) and sight (right) impairment.
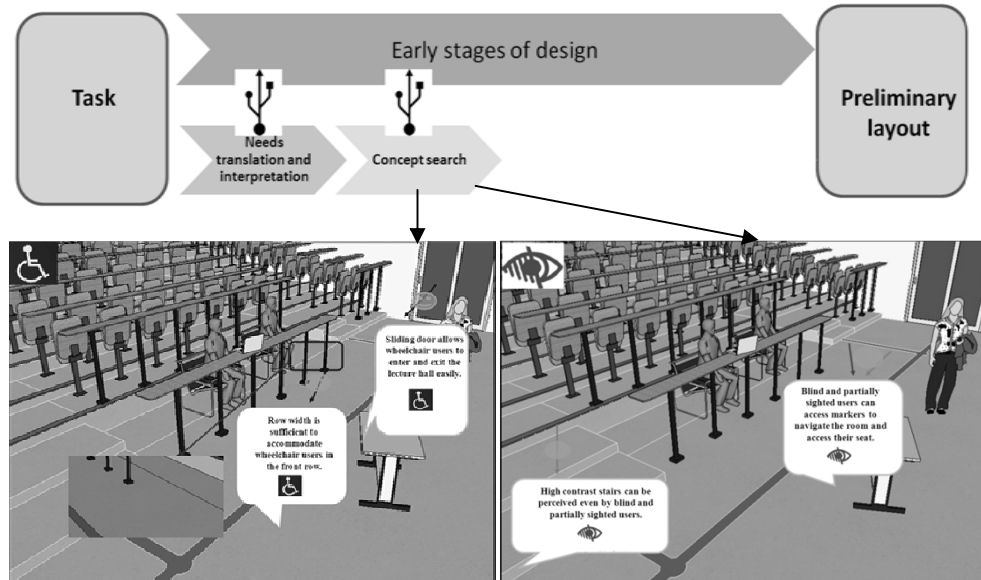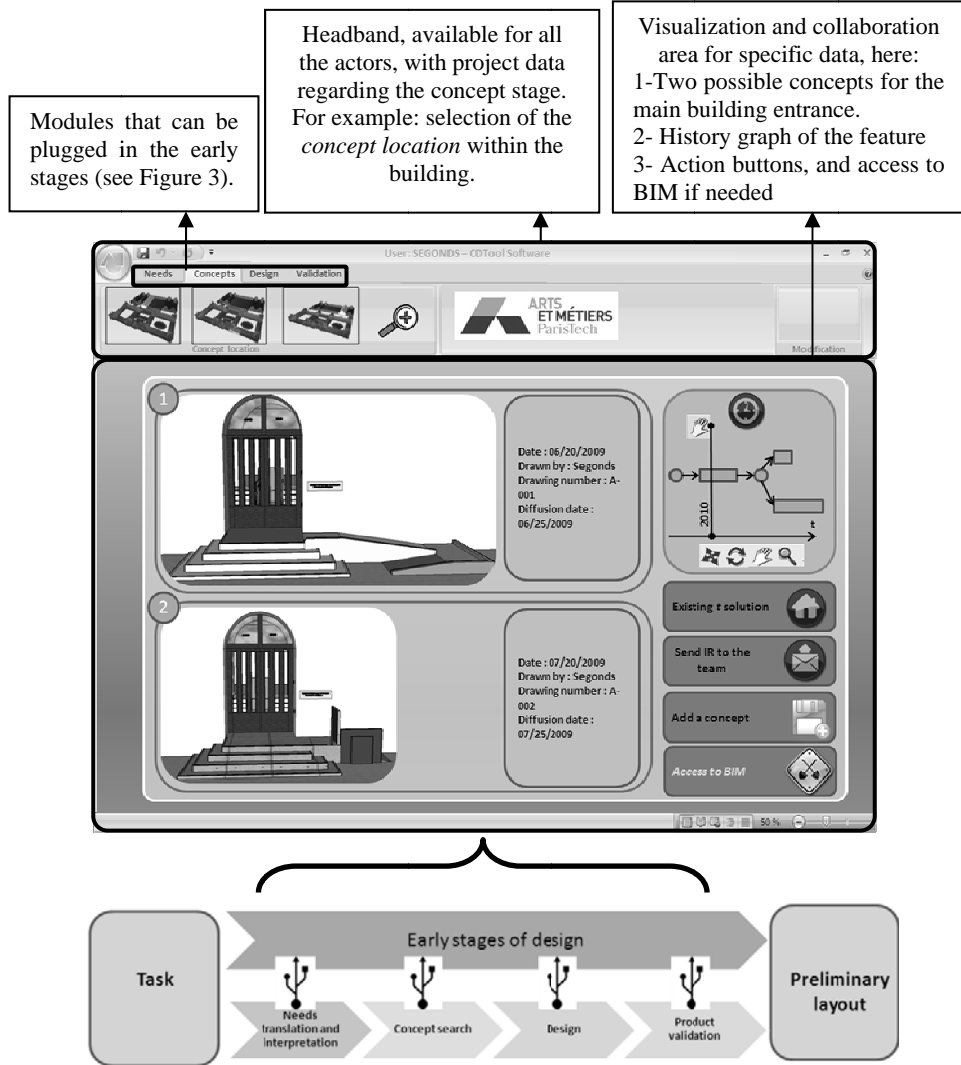
Figure 7 - Mockup of a screen from our proposed software suite, and position in the global framework