Activity theory and the practice of design: evaluation of a collaborative tangible user interface

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Abstract: BUILD-IT is a Tangible User Interface (TUI) developed to facilitate collaboration between a group of designers or planners seated around a table. We briefly describe a task analysis conducted to determine what the target users of the system do in the course of their work. The responses provided by 16 potential users are summarised as design insights. The system designed to facilitate dealing with these tasks, described in more detail by Rauterberg et al. [1] and Fjeld et al. [2], is then outlined. The remaining sections of the paper present an informal evaluation of BUILD-IT consisting of the first author's responses to questions selected from the Activity Checklist devised by Kaptelinin et al. [3]. The relationship between BUILD-IT and activity theory is a theme throughout the paper since tangible bricks – physical objects which users manipulate – bring behavioural ('objective') elements of activity particularly close to the decision-making, cognitive ('subjective') elements of activity involved in planning and design.

Keywords: Tangible User Interface; human–computer interaction; augmented reality; collaboration; planning; layout; usability; evaluation; activity theory; Activity Checklist.

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1 What designers and planners do: a task analysis

The first part of this section introduces the industrial partners and typical planning activities in those companies. The second part describes a task analysis [4–6] carried out with 16 expert planners from four enterprises engaged in design and planning. The final part discusses the responses obtained. This analysis was done in order to find out what potential users were doing and what they needed in a Tangible User Interface (TUI) meant to facilitate their collaborative planning activities.

1.1 Sample

Brief descriptions of the four enterprises which employed the 16 respondents of the task analysis may help establish the concrete context in which it was conducted. For the most part, these descriptions are based on the companies' websites.

Company A offers weld systems being used worldwide for the joining of automotive components and products. Custom designed weld systems for specific applications are built on a turnkey basis. Company A is the only equipment supplier for two of the most important welding technologies: the laser and the resistance roller seam welding process for tailored blanks. The use of tailored blanks is a new method to build body structures of cars. Two or more sheet metal pieces of different specification, thickness and shape are joined with laser or mash weld prior to being stamped into the desired car body part. The advantages are lighter cars, less curb weight, improved structural performance, stronger body, better absorption of crash energy, reduced parts count, easier assembly, and greater cost effectiveness.

Company B offers standard machines, modular machining system, and key modules. Typical standard machines are milling machine centres. Typical special machines are high output machining systems like rotary transfer machines and linear transfer machining systems for gear pumps in dialysis and parts for injection systems. Typical key modules are high-performance cutting tools and spindles.

Company C specialises in environmental technology. It builds and runs thermal waste treatment plants and supplies technology and know-how for flue-gas purification and by-product recycling.

Company D is a consulting firm that specialises in corporate design. It develops models and strategies with clients with the aim of promoting unmistakable corporate cultures. It promotes its clients' efforts to establish a visual identity, which strengthens the position of their brand in the market place. The company supports clients all the way from initial briefings to marketing and strategy assessment.

1.2 Procedure

The initial task analysis phase specified the *target technology*, i.e. the context, potential uses, expected benefits, and requirements of a future BUILD-IT system. Interviews based on five questions (Q1–Q5) were conducted with the 16 respondents from the four participating enterprises.

In these companies, computer-supported mediation of planning tasks plays an increasingly important role and rests largely on the shoulders of expert planners, defined here as highly skilled employees with many years of experience in activities such as cost estimation, technical calculation, production scheduling, capacity utilisation, and the use of modern manufacturing technology.

The task analysis was initiated by a brief presentation of the key features of the envisioned BUILD-IT system to the planning experts. One or two experts from each enterprise were then interviewed in depth about the context and how they currently carry out planning tasks (Q1), the tools currently at their disposal (Q2), the inadequacies of these tools (Q3), the benefits expected from BUILD-IT (Q4), and the concrete requirements they expected from a system like this (Q5). Both pre-CAD and CAD-based collaborative planning were of interest, i.e. the interviews covered traditional planning using two-dimensional pencil-and-paper representations and discussions, as well as single user computer-mediated planning.

The task analysis was carried out with certain boundary conditions in mind. When a computer application fails to function according to the needs and wishes of the users, it is often said that the initial task or flow analysis was 'inadequate'. However, Bannon and Bødker [7], rooted in the tradition of activity theory, point out that something more than readily verbalised activities often needs to be considered. An example of what they have in mind was videotaped in the course of our task analysis [8]. It shows an expert planner engaged in a discussion with two colleagues. Subtle aspects of the actions and operations of the three respondents in this situation are difficult to capture in a written description. There are limits to the degree it is possible to catch the tacit knowledge required in many skilled activities or the fluent execution of the actual work process. Bannon and Bødker [7] go so far as to suggest that we will never be able to give a full description of a task.

In general, potential uses of the proposed BUILD-IT system were perceived similarly by representative(s) of the four enterprises. Some uses identified by only one company are noted as well. The answers to Q1–Q5 were interpreted and formulated as design insights in terms of the five issues listed in the following results part.

1.3 Results

1.3.1 Aspects of the planning task likely to be supported by BUILD-IT

Information from all four companies suggested that BUILD-IT was perceived as having the potential to improve the assessment of client needs which is currently based on paper-and-pencil (printed material) methods. Similarly, the system was seen as potentially helpful in marketing services and products to CAD-specialists and planning experts.

1.3.2 Potential uses of BUILD-IT

For all four companies, potential uses suggested were the presentation of production plant solutions and computation of alternative solutions, increased presence on the internet and as a company employing virtual tools, and in communication between their marketing department and their CAD experts.

For one company, a potential use was in a new project for rotary transfer machining, a system especially suited for multi-operation machining, being cost efficient, offering high volume production, covering work pieces in sizes of up to 120 mm × 120 mm × 120 mm, and offering high precision and production rates. The same company saw uses in the presentation of offers and in the planning of complex production plants using virtual models. For another company, potential uses included the facilitation of three-dimensional (3D) representations for internal meetings, and of collaborative planning within the company and with clients. A third company saw a specific use in internal pre-CAD planning taking place prior to the use of a CAD system.

1.3.3 Expected benefits of BUILD-IT

The respondents from all four enterprises hoped that BUILD-IT would reduce costs; that it would facilitate marketing, production, and collaboration; and that it would aid in tasks involving visualisation. The reasons they indicated for expecting savings included earlier discovery of mistakes in the planning process and reduced need to travel or to engage in video conferencing. Marketing should be facilitated by 3D representations, hands on demonstrations, and dramatising the sales presentation in general. In particular, it was expected that people normally not used to think in three dimensions would find it easier to do so. The production process was expected to be enhanced by the ability to generate different product versions and by easier implementation of standard solutions and processes. For example, earlier plans for welding lines solutions might be more easily browsed by potential clients in the search for a suitable sketch. As for the collaborative process, the use of large displays, a less techno-centric perspective, reduction of complexity, and mediation of internal discussions were seen as benefits.

1.3.4 User interface requirements of BUILD-IT

Interface requirements concerning system configuration, system set-up, versions, real-time data import, model height adjustment, real-time data export, accessibility, and sales conditions were expressed. Here too, the information from the four enterprises was essentially the same.

More specifically, the following requirements were formulated: access to a set of adjustable process security parameters, the capability to distributed work, typically between a head office operating in master mode and an overseas department in slave mode; a portable version of the system and a laptop version for marketing activities; CAD models or model parts combined with Product Data Management (PDM) data like sheet thickness; a real-time connection to a database containing previous offers in PDM format; interactive control of production parameters like material input and product output; options to set model height and the visualisation and handling of layers (e.g. the layers could be coloured differently and represent floors in a building or layers of pipelines in a chemical factory); the positioning of models at these layers combined with an analogue height-scale tool; quick export of 3D images as electronic files or in print; a large screen; and easy-to-learn and easy-to-handle software. Finally, the possibility to lease or rent a system was required.

1.3.5 Data interface requirements of BUILD-IT

The data interface requirement of the system which emerged in the course of the task analysis included the following: reliance on integrated use of fax, intranet, and internet (since current contact with clients still depended on standard office tools and, as result, on fax more than CAD, and since specifications and data sheets were still mainly communicated using intranet and e-mail), integration with in-house programs for Microsoft Excel computations, integration with Product Data Management (PDM) tools (since customer-driven design is mostly supported by them to describe virtual models); simultaneous interaction with a two-dimensional plan view; a three-dimensional side view and a height view; and, finally, portability across different operating systems and platforms.

To illustrate the data interface requirements specific to one company: Its personnel wanted to work with EUKLID, AutoCAD, and Unigraphics – software already in use at its head offices. They required support for a separate CAD standard used in the USA, for the Prime Medusa CAD system, and for an in-house variety of AutoCAD.

2 The BUILD-IT system

The first part of this section introduces important research concepts, such as Human–Computer Interaction (HCI), Tangible Users Interfaces (TUIs), and computer-supported collaborative work (CSCW). The second part shows the process from task analysis to the BUILD-IT system. The third part gives further details on the system and offers a few examples from the design process, and the final part introduces some important concepts related to working in real and virtual environments.

2.1 Introduction

Human–Computer Interaction (HCI) is

> "a discipline concerned with the design, evaluation and implementation of interactive computing systems for human use and with the study of major phenomena surrounding them." [9, p.5]

Tangible interfaces

> "give physical form to digital information, employing physical artifacts both as 'representations' and 'controls' for computational media. Tangible User Interfaces (TUIs) couple physical representations (e.g., spatially manipulable physical objects) with digital representations (e.g., graphics and audio), yielding user interfaces that are computationally mediated but generally not identifiable as 'computers' per se." [10, pp.916, 917]

The present evaluation of the HCI aspects of BUILD-IT is founded on activity theory, regarding people (computer users, developers, and managers) as subjects engaged in purposeful activities. These activities are mediated by various tools. Tools may be physical, mental, or virtual; and they are specific to the context in which they appear. Activity theory served as a framework guiding the steps involved in designing BUILD-IT, it provided useful concepts to better understand this process, and it was the theoretical basis for the Activity Checklist employed to evaluate the BUILD-IT system as a tool for computer-supported collaborative work (CSCW).

2.2 From task analysis to the BUILD-IT system

The design insights obtained from the five task analysis questions made it possible to shape our application of BUILD-IT for the potential users of the four enterprises involved in this work. It first led to the prototypical BUILD-IT system [1,8] and later to the complete BUILD-IT system [2,11].

In general, it seemed that the respondents of the task-analysis were indicating that BUILD-IT could accommodate sharp divisions of labour between end-users, and serve as tool in marketing and internal communication and planning. One fruitful aim which seemed to emerge was to design the system to support the development of complex production plants by enhancing its ability to facilitate interaction with 3D information. It seems difficult for clients of designers and planners to imagine what the outcome of the planning process will actually look like. The task analysis responses suggested that BUILD-IT could facilitate communication and formation of concrete expectations on the part of clients.

BUILD-IT is a tool for collaborative planning, making it possible for many participants to work at one table, to discuss, and to try out different options. Hence, group work may be facilitated without having to modify and refurnish offices.

After the BUILD-IT prototype was realised, it was tried out with designers from the two industrial partners producing assembly lines and plants. These designers regularly see their customers, and are aware of what a mediating tool should look like.

One illustration of how the task analysis impacted on the design process turning the prototypical into the complete BUILD-IT system involves the navigation system. Potential users indicated a specific need for navigation of the virtual setting, construction site, or 'scene' within a planning session. In our design process, we first focused on the navigation of the side view. An initial idea to enable side view navigation – operations such as panning, rotation, and zooming – was to use an animated human model to control the side view so that system users would get the same perspective as the virtual model. In the case of several models, one of them would be selected by system users and tagged as the active model. This active model would control the perspective of the side view.

However, within the multimedia framework available, models of humans could not be animated sufficiently well. Instead, a camera was employed to control the viewpoint and zoom on the virtual setting [11,12]. Further illustrations and details are offered in Fjeld [13].

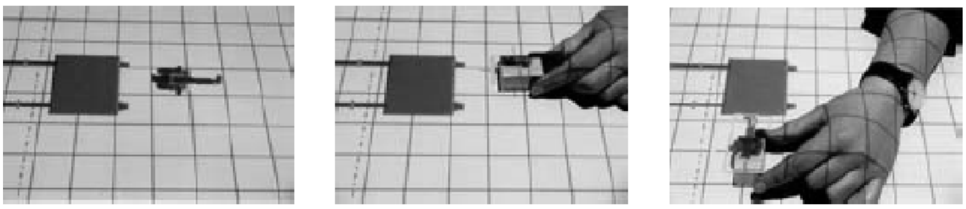
2.3 The BUILD-IT system

The remainder of this paper concerns the complete BUILD-IT system, the end result of a process described in several publications [1,2,8,11–19] and illustrated in Figures 1–3. It is a TUI which incorporates computer vision technology and concepts from the field of augmented reality, as well as collaborative groupware for planning and layout tasks employing 3D graphics, and it can be thought of as a pre-CAD system.

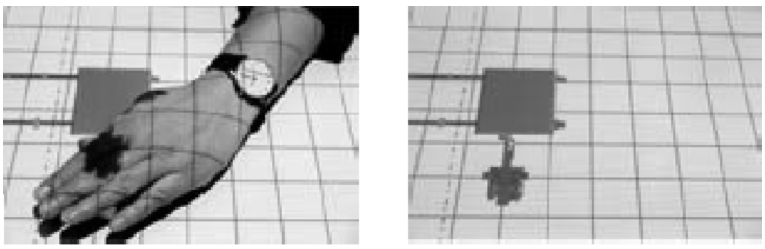
Figure 1 The Tangible User Interface system: (a) Cabinet, table, chairs, and screen; (b) interacting in the BUILD-IT system; (c) menu with navigation tools and user's hand engaged in brick-based model handling

(a) (b) (c)

Figure 2 Typical interaction sequence showing: (a) initial situation; (b) model selection; (c) model placement; (d) model de-selection; and (e) final situation

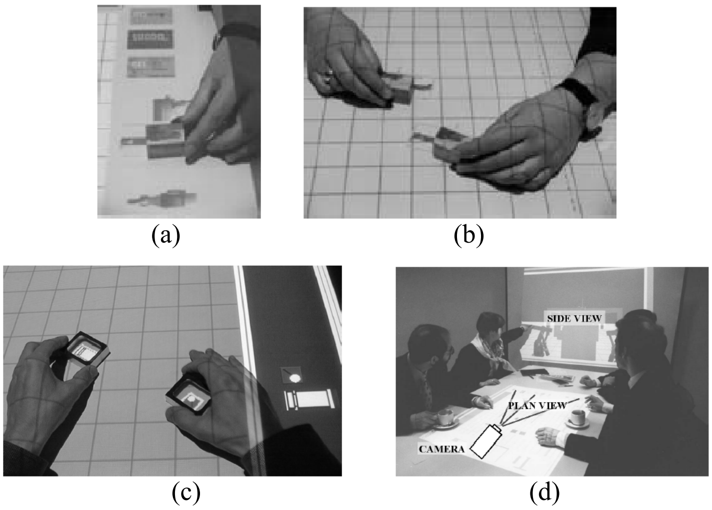


(a) (b) (c)



(d) (e)

Figure 3 Four typical cases: (a) model selection in the menu; (b) two-handed interaction in the plan view; (c) user's left hand on the camera and user's right hand on the zoom; (d) and side view navigation (camera redrawn)



As described by Fjeld et al. [2, pp.162, 163], BUILD-IT consists of a high-capacity PC, a mirror, a table, chairs, and a screen (Figure 1(a)). The personal computer (PC) is housed in a cabinet somewhat taller than a lectern and placed at one end of the table, facing the screen at the other end. The hardware also includes two projectors, a video camera and an infrared light source. The design team or single user sit at the table on which the object of interest, such as a production plant or a piazza, evolves (Figure 1(b)). The users manipulate elements called bricks which assume forms like rectangular and cylindrical blocks (Figure 1(c)). Infrared light is reflected from the reflective surfaces of the bricks. As they are moved around on the tabletop, their positions are tracked, image-processing software is applied, and the 3D models they handle are shown in horizontal plan view from above on the tabletop and in vertical side view on the screen. The projector providing the plan view is in a fixed position, the projector providing the side view can be moved around on the tabletop.

The design process took into account that evaluations of HCI design principles showed that "perception and action spaces must coincide in time and space" [20, p.206]. This insight has led to a new concept of the so-called natural user interfaces employing projected light and pattern recognition [21] which was implemented in the BUILD-IT prototype [1,8].

2.4 Concepts and terminology

In the context of BUILD-IT, it is essential to carefully consider terms like 'real', 'physical', 'virtual', 'digital', 'tangible', and 'graspable'. Eisenberg et al. [22] defined virtual artefacts as non-physical. They noted that

> "friends meet in virtual 'chat rooms'; children are educated in virtual classrooms; academics attend virtual conferences. The products of computer-based work and education – spreadsheet models, educational simulations, Web-based art galleries – likewise have an almost relentlessly intangible nature." [22, p.159]

This led them to make a polar distinction between things virtual and things physical and tangible in their approach to the "integration of computers and real-world objects" [22, p.159]. Eisenberg et al. [22] also present the alternative position focusing on convergence rather than opposition of the real and virtual worlds.

Opposite poles or convergence of the real and virtual worlds? What users perceive as 'real' is treated in more detail at a theoretical level by Fjeld et al. [2], but in the context of this more practical work, the task of redefining what is 'real' and what is 'virtual' leads into a philosophical quagmire we devoutly seek to avoid. We prefer not to deal with the term 'real', and following Eisenberg et al. [22] understand 'virtual' to mean something opposed to the physical and tangible.

This approach is consistent with our activity theoretical framework focusing on how purposeful activities are mediated by various tools which can be physical, mental, or virtual; and which rarely resorts to the use of the contentious term 'real' [23]. Since we do not study mental (cognitive) tools in this project, this leaves us with a focus on physical and virtual tools. In our project, the potential for interaction was facilitated by physical tools, by virtual tools, but mostly by a combination of both.

3 Evaluating BUILD-IT: user types and question categories

The evaluation of BUILD-IT involved three types of users and four categories of questions. The results of the evaluation should be considered in the context of the 3 × 4 contingency Table 1.

Table 1 4 × 3 contingency table of the Activity Checklist question categories and the three user types

Thrust of the four Activity Checklist question categories as applied to BUILD-IT	*User type*		
	Developers	*Expert-User*	*End-Users*
Means and ends: Does BUILD-IT facilitate the achievement of user goals?	Developers collaborated well. However, most development and testing was command-based, not using brick-based input	Expert-users were able to carry out planning tasks and configure the BUILD-IT system	After a short instruction period users were able to perform required tasks
Environment: How well does BUILD-IT fit into the present work environment of the users?	Good fit for team-based code development. However, the multimedia library (MET++) is not standard software and hence difficult to develop	Good fit since side view supports collaborative planning. However, expert-users are more familiar with the 2D plan view	Medium fit since end-users find it hard to use the side view in task solving
Learning: What training demands are made by BUILD-IT?	Intensive training was required to develop and modify the code of the system	A few days' training were required to set up, configure, and use the BUILD-IT system; far less than for CAD systems	Empirical studies showed that about 15 minutes were required to perform required tasks
Development: How does BUILD-IT affect the development of an organisation?	The group of developers was pleased to work with the BUILD-IT technology. Team-work functioned well	An informal evaluation suggests that expert-users were able to carry out a team-based planning task	The Engeli study indicates that end-users were able to carry out a team-based planning task

The first part of this section presents the three user types considered and indicates the origin of our empirical data. The second part introduces the Activity Checklist [3] and relates it to Tangible User Interfaces (TUIs). Drawing on various forms of information obtained from the users and previous studies, the four categories of questions selected from the checklist are answered. Hence, the four subsequent parts give an extensive, though informal, evaluation of the BUILD-IT system.

3.1 User types: developers, expert-users, and end-users

The evaluation of the BUILD-IT system must take into account the requirements of three potential user types: the developers, expert-users, and end-users which are distinguished in Table 2 in terms of who they are, their target technology, their target actions, and who interpreted the information they provided.

Table 2 User types: developers, expert-users, end-users

Defining features	*User type*		
	Developers	*Expert-User*	*End-Users*
Who are they?	The 8-person BUILD-IT development team	16 planners and designers from four enterprises	Respondents of the Engeli and Fjeld usability studies
What is their target technology?	The BUILD-IT system with all advanced features described	The BUILD-IT system with most advanced features described	The BUILD-IT system with a standard set of model handling and navigation tools
What are their target actions?	System design, development, testing, and usability evaluation	Planning, including preparation of planning sessions by setting system parameters and menus	Brick-based solving of predefined search and positioning tasks
Who interpreted the information provided?	The 8-person BUILD-IT team were both respondents and interpreters	The responses of the expert-users were interpreted by the BUILD-IT team as a group	M. Fjeld interpreted the responses obtained and/or reported in the Engeli and Fjeld usability studies

Target technology is a specific technology serving as tool to carry out target actions. The collective experience of the BUILD-IT development team, a group of eight people including computer scientists, mechanical engineers, and work psychologists, was the basis of the answers reported here from the perspective of the *developers*. User feedback from planners of the four participating enterprises is the basis of the answers from the perspective of the *expert-users*. These partners were mostly interviewed as they used BUILD-IT to interact with a layout from their own practice. Finally, empirical data and user feedback from test subjects in three experiments enable us to answer questions from an *end-user* point of view. The first experiment was an exploratory architecture competition involving five groups of students [24]. The second experiment compared BUILD-IT to other tangible tools and involved 30 test persons [19]. The third experiment was a comparative study of alternative navigation methods and involved 16 test persons [18].

To illustrate our understanding of *activity* and *actions*, two examples are offered. The first example is designing the layout of a welding line including four robots and a welding machine. This activity may require two persons for a week. Typical actions within this activity would be to discuss alternative layouts, to position a robot, to compute a production rate, and to consult welding guidelines. The second example is the layout of an office, which may require a single person for a day. Actions within the design activity in this case would be to position chairs, to control the relation between the work stations and various light sources, and to estimate the total costs.

3.2 The activity checklist sample questions

Hasan [25] refers to a handful of instruments relying on activity theory to support the design processes in Human–Computer Interaction (HCI). Among these is the Activity Checklist by Kaptelinin et al. [3] which is closely linked to problems raised by practitioners in the field. A section of the Activity Checklist called the Sample Questions is designed to help evaluate systems in early phases of development. Since TUIs and the integration of physical/tangible and digital/virtual realms are still at a prototypical level, the Activity Checklist seemed a useful means to the end of evaluating the BUILD-IT system.

The Activity Checklist relies especially on the activity theoretical principle of mediating tools. A tool mediates an activity, thereby connecting a human being not only to the world of objects – his or her physical surroundings – but also to other human beings. The specific aim of our project was to evaluate different ways to enrich computer-mediated activity by using tangible tools.

The Sample Questions are meant to analyse how people use, or will use, computer-based technology. Here they were used to summarise and predict how well developers, expert-users, and end-users can employ the BUILD-IT system. Although our system is groupware, the evaluation mostly focused on single users. This consideration determined the choice of questions from the Sample Questions section of the Activity Checklist. Such selection of a subset of questions seems to be consistent with the recommendation of the authors that their instrument not be used in a mechanical (linear, additive) fashion. They recommend, for example, that "practitioners using the tool should look for patterns of related items, even if these items belong to different sections" [3, p.33].

As indicated earlier, the Activity Checklist questions were primarily answered by the first author who was most intimately involved in the day-to-day design process. They were changed slightly to focus them on BUILD-IT by substituting 'BUILD-IT' for both 'target technology' and 'system'.

The Sample Questions consist of four categories, each representing a different approach to describing the target technology and how it supports target actions. The four categories are indicated in the overview in Table 1, together with our interpretation of the general thrust of each as it might apply to BUILD-IT. In the following, each category is examined separately. While some issues were relevant to all user groups, others proved relevant to one or two only. In the latter case, this is specified.

3.3 Means and ends

The *Means and ends* category contains questions which inquire into '[M]eans and ends – the extent to which the technology facilitates and constrains the attainment of users' goals and the impact of the technology on provoking or resolving conflicts between different goals' [3, p.33]. It should be noted here that the first two questions evaluating means and ends were of particular relevance to our design process and are, therefore, dealt with in greater detail than the others.

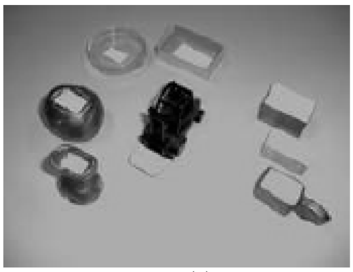
3.3.1 Is there any functionality of the BUILD-IT system which is not actually used? If yes, which actions were intended to be supported with this functionality? How do users perform these actions?

When there is a functionality of the system which is no longer used, it usually was a once used part in the ongoing design process. Hence, this question is answered by giving examples of various steps in our design process, first from the design of *physical tools* then from the design of *virtual tools*. Physical tools are tangible objects sitting on the tabletop and operating on the virtual models. Virtual tools are selected from the menu and used within the plan view.

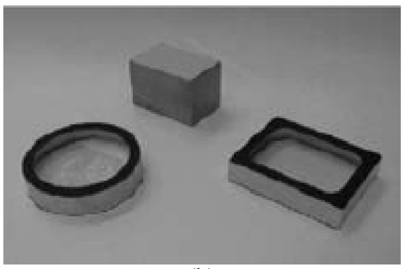
The issues which arose in the development of physical tools centred on *brick form* and *physical height tools* [2,17]. A brick is a generic, physical handle with a reflective surface used to handle a virtual model; a height tool is a specialised physical tool used to set the height of a virtual model. There were also other hardware aspects of the project, such as the design of the cabinet with a mirror, the integration of video camera and infrared source into one physical unit, the use of projectors, and the development of a portable system [13].

Brick form was relevant to all user groups. The original intention of using differently shaped bricks was to offer more and richer information in the physical realm. In theory, differently shaped bricks could have represented specific virtual models (e.g. a chair, a machine) or specific virtual tools (e.g. set rotation, set zoom) as illustrated by Fjeld et al. [17]. However, an early user study showed that participants preferred a simple rectangular brick to more elaborate forms. Hence, different brick forms constitute a functionality that was not used. To enable the same actions as those potentially offered by differently shaped bricks, a larger variety of virtual models and tools were offered as shown in Figures 4 and 5.

Figure 4 (a) Our design process started with differently shaped bricks; (b) proceeded to a subset of a few forms; (c) and ended up with a single form



(a)



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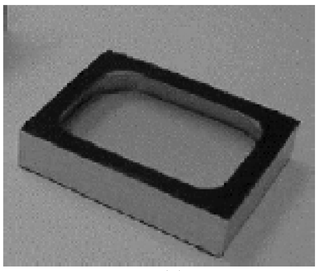
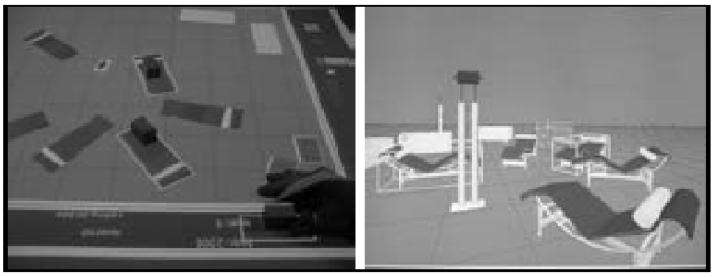


(c)

Figure 5 (a) Our design process for height tools started out with physically based tools; here a slider with up-down buttons and analogue height display and (b) proceeded to a height slice; here with two selected models prior to height selection and (c) after height selection

(a)



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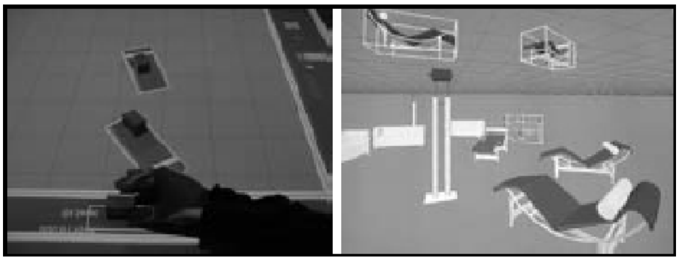

(c)

Physical height tools are relevant to developers. They were used to explore alternative ways to introduce layers and floors in order to set the height of a selected set of models. The insight and technology acquired using these tools were implemented in a so-called height slice [17]. The height-slice is a virtual tool and enables all the functionality offered by the physical height tools (Figure 5).

Considering the whole project, most functionality was designed and implemented in software rather than hardware, typically leading to virtual tools. The major tangible aspect of these tools is that each one is handled by one – sometimes two – rectangular bricks. In the following, we give examples of a few virtual tools which were part of our design process but which are not in current use. We then show how the actions are currently performed.

The *Brick-model locking mechanism* is relevant to developers. At the moment of selecting a virtual model with a physical brick, a planar relation – in terms of position and rotation – is established between the brick and the virtual model. This locking mechanism determines how a physical brick and a virtual model stay connected from the moment of selection until the moment of de-selection. How they connect may vary in terms of angular orientation and alignment. This functionality was intended to enable effective model handling. However, in the final system, one single locking mechanism is used all the time. This proved to be sufficiently effective for the target actions addressed in our research.

Real-time communication with Computer-Aided Design (CAD) systems is relevant to developers and expert-users. This functionality was meant to offer real-time bi-directional communication of virtual models and planning results between the BUILD-IT system and any CAD system [16]. Such functionality would have been of great use in an industrial setting. In one case, real-time transfer of virtual models from a specific CAD system to the BUILD-IT system was achieved. However, it would have required significant effort to make such communication bi-directional and reliable, and to suit most CAD systems. Hence, importing new virtual models from, and exporting the result of a planning session to a CAD system are carried out manually before and after planning sessions.

Model annotation is relevant to developers and expert-users. This functionality enriches virtual models with information such as part identity and price, typically coming from a Product Data Management (PDM) database [16]. It was implemented in a few models and for limited amounts of information. However, full-scale functionality would have required significant implementation and testing to prove effective in use and was therefore not pursued. In the current system, simple textual annotation can be loaded from a configuration file.

Side view navigation enables viewpoint control of the side view perspective. Viewpoint control includes pan, rotation, zoom, tilt, and roll [12]. However, in a pilot study, users reported that they found the adjustment of side view tilt and roll disturbing. The reasons given were the loss of a horizontal orientation and feeling lost in the virtual setting. Hence, the control of tilt and roll is not offered. The exploration of a virtual setting is still performed adequately through the control of pan, rotation, and zooming [11,18].

3.3.2 What are the basic limitations of BUILD-IT?

Limitations of the current system pertain to all three kinds of users. Some of the limitations may be resolved through development and testing. Others will dissolve with the advent of more standardised and higher performing PCs.

Typical limitations which may improve through technological advances are slow image processing leading to slow brick detection. Another limitation is the latency in output as the update of 3D graphics is still time consuming. The portability of the system software is a further issue, given the need for video frame grabbing and graphics cards.

A limitation which is more inherent in system design is the top projection applied. Using such projection, a user’s hands moving above the table may hamper brick detection. Hence, virtual models may be de-selected inadvertently. Such de-selection may have consequences such as lost accuracy and breakdown in the navigation of a virtual setting.

Maintainability of the software is not only an issue with high relevance to developers, but also with implications for users. The source code was written in C++ and later in Java 3D. Both languages require high-level programming skills. However, most criteria for software maintainability are language independent, for instance: the code must have consistent structure, be modular, well commented, contain some sort of exception handling, be portable from one compiler to another, and use intelligible naming. Since the BUILD-IT system was developed mainly as a research platform and not as an industrial product, these criteria were not met in every case. Table 3 gives our impression of the degree to which the criteria of maintainability of the software and the hardware were met.

Table 3 Apparent levels at which criteria for maintainability of the software and hardware were met

Criteria for the software	*Level attained*
Modularity: Consequent use of functions, procedures, and files	Very high
Well-commented	High
Intelligible and consistent use of names	High
Explicit exception handling	Medium
Portability between different compilers and processors	Low
Transparency to major virtual model formats	Low
Portability between different 3D graphics cards	Low
Portability between different video frame grabber cards	Low
Code has been reviewed	Very low
Low-level configuration of PC is hardly required (e.g. dll-files)	Very low
Criteria for the hardware	*Level attained*
Adjustment of the video camera lens	High
Positioning of the video camera box	High
Robustness of the mirror	High

3.3.3 Is it necessary for the user to constantly switch between different actions and activities?

First, if unwanted de-selection occurs, it might be necessary to switch between different actions. This may typically happen when users combine navigation and model positioning. Second, in order to load a new planning session, it is necessary to quit the application and start up with another set of virtual model files.

3.3.4 If yes, are there 'emergency exits' which support painless transition between actions/activities, and, if necessary, returning to previous states, actions or activities?

First, in the case of unwanted de-selection while performing navigation, it may be difficult to return to the previous state. Second, to store the current situation of a planning session, there is a manual file storage capability which can be operated from the system menu. There is also an automatic file storage capability which runs at regular intervals. This time interval can be set by the user in a system configuration file. Finally, to return one or several steps in a planning session, an undo function was implemented in a prototypical version. This undo function was not put into regular use.

3.4 Environment

Kaptelinin et al. [3] label this category of Sample Questions *Social and physical aspects of the environment*. The questions focus on the "integration of target technology with requirements, tools, resources, and social rules of the environment" [3, p.33]. We chose to answer these questions for two major domains studied in this project, namely *production plant layout* and *architecture*. We relate the answers to the major features of the BUILD-IT system: tangible bricks, co-location, plan and side views, two-dimensional and 3D model representation.

3.4.1 *Are concepts and vocabulary of the BUILD-IT system consistent with the concepts and vocabulary of the domain?*

In production plant layout, something like a side view is hardly ever used. The usual perspective is the plan view offering two-dimensional models. This means that the BUILD-IT system offers a certain redundancy to planners. The concept of tangible bricks is consistent with physical downscaled models of robots, welders, and other production components in production plant layout. Architects appreciate the potential for teamwork of a colocated system using tangible bricks combined with a quasi-3D side view for teamwork [24,26].

3.4.2 *Is BUILD-IT considered an important part of work activities?*

Paper drawings still play a major role in both production plant layout and architecture. However, computer-supported collaborative design has been in use for some years and has increased in importance. Therefore, planners and architects mostly consider novel interaction concepts – like the BUILD-IT system – with great interest for their own work practice.

3.4.3 *Are computer resources necessary to produce a certain outcome integrated with each other?*

This question can be answered separately for the preparation preceding a planning session and the work following a planning session. The answers apply to both planners and architects.

Before a planning session, 3D virtual models must be loaded into the BUILD-IT system. The creation and modification of virtual models for the BUILD-IT system require a 3D modelling tool. The modelling tool must export 3D models in the format of Virtual Reality Modeling Language (VRML).

After a BUILD-IT planning session, additional detailed planning is required since BUILD-IT is a pre-CAD system. Pre-CAD systems offer less precision and fewer interfaces to standard formats than CAD systems. We have previously discussed how real-time bi-directional communication with CAD systems was explored but not offered in the final system version. Instead, users manually transfer the outcome of a planning session into a CAD system to continue there with more detailed planning.

3.4.4 *Are characteristics of BUILD-IT consistent with the nature of the environment (e.g. central office work vs. teleworking)?*

The environment for planning and architecture will mostly be shop floors and design studios. The BUILD-IT system may only be partially integrated in, and with, such environments. The reason is that it runs on a proprietary computer on which, basically, no other major applications can be installed. Hence, for remote collaboration between different shops or studios, video-conferencing software must run on separate computers. As for other office equipment, the system requires two projectors. The installation of the plan view projector is fixed. The other projector, giving the side view, can easily be moved about and hence used for other purposes.

3.5 Learning

The third category of Sample Questions is labelled *Learning, cognition, and articulation*. Here, the focus of inquiry is on "internal vs. external components of activity and support of their mutual transformations with target technology" [3, p.33]. Learning and cognitive support of tools was examined in a study comparing BUILD-IT with other tangible tools [19]. Learning and spatial cognition was examined in a second study comparing other navigation methods within the BUILD-IT system [18]. The answers recorded here draw on the empirical data and insight from these studies.

3.5.1 Is the whole 'action life-cycle', from goal setting to the final outcome, taken into account and/or supported?

End-users required about ten minutes of instruction to be in control of basic functionality such as model selection and composition. For expert-users, the installation and use of the system was described in a manual [27]. This manual has not been usability tested. Personal instruction probably remains a necessary complement.

3.5.2 Is externally distributed knowledge easily accessible when necessary?

Externally distributed knowledge can be available in the form of other workers, in tools, and in documents. To concretise this question, we examined knowledge as it appears in people at the same work place, physical tools at hand, paper documents, digital documents, and virtual models. Table 4 shows an informal comparison between accessibility of sources of knowledge when using standard PC-based procedures and BUILD-IT.

Table 4 Comparison of accessibility levels of externally distributed knowledge

	Accessibility Level	
Source of knowledge	*PC and standard software*	*BUILD-IT*
People at the same work place	Medium	High (around the table)
Physical tools, e.g. pen	Medium	High (at the tabletop)
Paper documents, e.g. drawings	Low	High (within plan view)
Electronic document files	High	Low (requires keyboard)
Virtual model files	Medium	Medium (if in menu)

3.5.3 Does the BUILD-IT system provide representations of users' activities, which can help in goal setting and self-evaluation?

This question can be answered on two levels. First, we considered how users' activities could be represented within a planning session. Since multiple bricks can be used simultaneously, the bricks easily serve as a kind of external memory. Such external memory can facilitate cognition and goal setting and thereby support self-evaluation.

These effects were observed by Fjeld et al. [18]. Second, we considered how users' activities could be represented after a planning session. The system can save planning results – a set of models with their position and rotation – to an external file. This is done automatically, for instance, every five or ten minutes and can also be triggered by the users. Also, selecting a print button in the BUILD-IT system menu prints the current planning results. Drawing on the combination of saved and printed results, users may examine the outcome of their activities and be prepared to come back to the system for further planning.

3.6 Development

The last category of Sample Questions covers *Development*, that is, the developmental transformation of the above components as a whole. In this project, long-term effects of using the BUILD-IT system were not examined. Hence, Sample Questions relating to long-term effects were not considered.

3.6.1 What are the consequences of implementation of BUILD-IT on target actions?

In collaborative planning, the users are located around a table instead of using their individual PC or CAD station. We still have not examined whether this work style is more effective and whether agreement on common concepts is reached more efficiently. For further reference, the effect of colocation in the use of TUIs has recently been examined in depth by Kiyokawa et al. [28]. They showed how to locate a physically shared task space in relation to its users in order to efficiently support their design process.

3.6.2 Did expected benefits actually take place?

The research benefits expected from this project were generally attained. An up-and-running TUI was realised and extensive usability studies were carried out using this TUI. The benefits for single user problem solving using the BUILD-IT system were quantified and illustrated [18,19]. However, the benefits for collaborative planning still remain to be examined and quantified. Finally, a theoretical framework for the design of TUIs was established and summarised in a set of TUI design guidelines [2].

3.6.3 Did users have enough experience with the BUILD-IT system at the time of evaluation?

In the user studies carried out [18,19], the time to learn how to operate the system was controlled and proved to be sufficient. The learning effect within these experiments was also quantified and discussed there. The results showed that a relatively short time of instruction was needed to enable novice users to perform relatively complex tasks. The results also indicate that some learning took place throughout the experiments, but this was not significant.

3.6.4 Did the BUILD-IT system require large time/effort investment in learning how to use it?

This question must be answered for each of the user groups separately. For the developers, learning the system in terms of programming and (re-)configuration was a lengthy process, and was only achieved by a couple of the team members. It would have been advantageous if most of the team members had known how to program the system. For the expert-users, learning the system was part of the process of being introduced to it. For the end-users, the usability evaluations show that the time needed for end-use of the system is a matter of ten minutes.

To conclude this discussion of the answers to the selected Sample Questions of the Activity Checklist, some general points are worth noting. First, a background in activity theory is useful, perhaps necessary, in answering these questions. Second, to assure that all issues of importance are covered, it might have been wise to use all questions. Third, much depends on who asks and answers the questions. In the case of this project and when all is said and done, it was the same person, namely the first author. This is essentially a qualitative study, a quantitative study would involve more systematic interviews of representative samples of each user type. This might require reformulation of the questions so that all users can understand them. Fourth, it is a good idea to supplement the qualitative answers to the questions with systematic results that can be presented in tables or graphs when this is possible.

4 Implications of BUILD-IT for the design and use of Tangible User Interfaces

Drawing on various parts of the BUILD-IT technology presented here, a team at the Technical University of Clausthal developed a *TU Clausthal Planungstisch* [29]; another group at the Fraunhofer Institute for Manufacturing Engineering and Automation (IPA) in Stuttgart has developed the *Intelligent Planning Table* [30]; at the Technical University of Eindhoven work has been done on the *Visual Interaction Platform* [31,32]; and at the Technical University of Chemnitz a fourth group is working with another *TU Chemnitz Planungstisch* [33].

At the same time, the BUILD-IT system competes with a variety of other frameworks for tangible interaction [10,26,34]. The question arises, "Which part of the knowledge acquired in this project is currently most valid and relevant for human resources development?". More specifically, which design insights and empirical results gained in the course of this project apply to future design, evaluation, and use of Tangible User Interfaces (TUIs)?

This question can be approached from various vantage points from which we chose two. The first part of this final section focuses on technical and implementation issues, in particular, the enabling and limiting features of software and hardware. Focusing on Human–Computer Interaction (HCI), the second part considers the effectiveness and efficiency of the interaction facilitated by our design.

4.1 Technical and implementation issues

There is a series of technical issues still to be addressed in the design of TUIs. The dominant position of PCs represents one major challenge. Performance issues in computer graphics and image processing represent another. Innovative technical solutions to the design of TUIs will also be touched upon in this part.

Most potential users of TUIs are already users of graphical user interfaces, where much of the interaction employs the desktop metaphor. Therefore, on the one hand, standard functions – such as open, save, save as, quit, exit, copy, delete, and paste – must be taken into account in future TUI design. On the other hand, it should remain a priority to avoid the use of mouse and keyboard as far as possible. This represents a major challenge. For instance, how can users efficiently write a file name without using the keyboard?

While the challenges met in developing the BUILD-IT system were mostly of a technical nature, the process of turning it into a commercial product would require a wider scope. More attention would have to be paid to compatibility in order to cope with standards set by the Virtual Reality Modeling Language (VRML) and Computer-Aided Design (CAD) communities.

For future software development, object-orientation, quality measures, modularity, re-use, and portability are factors of utmost importance. The further use of a non-standard multimedia framework such as MET++ [35] will have to be weighed against the benefits of standard 3D libraries such as those offered by Java 3D.

The development of fluid interaction and navigation [13] – which enhance the user experience – also has a technical side, as they rely on efficient brick tracking, image analysis, and graphics updating. For instance, brick tracking may either employ computer vision or electromagnetic techniques. The latter has been implemented in a novel TUI called *Sensetable*, which "electromagnetically tracks the positions and orientations of multiple wireless objects on a tabletop display surface" [34, p.253]. *Sensetable* offers two fields of application: chemistry and system dynamics simulation. The creators of this TUI state that it offers advances over vision-based tracking. First, "the system tracks objects quickly and accurately without susceptibility to occlusion or changes in lighting conditions", and second, "the tracked objects have state that can be modified by attaching physical dials and modifiers" [34, p.253]. Technologies like those advanced by Patten et al. [34] and Arias et al. [26] may point to promising TUI applications in the future.

4.2 Human–Computer Interaction issues

In the design of effective TUIs, many HCI issues also remain unresolved. Many have been noted earlier in this paper, what follows is a summary.

First, it is apparent that tangible bricks may be seen with equal justification as *part of the interface* and as an *extension of the user's hand*. For instance, a keyboard is more a part of the interface, while a pen-like input device is more like an extension of the user's hand. This distinction calls for further investigation and help may be found in the work of Bateson [36] and Gibson [37]. These researchers have developed theories for human perception related to physical tools which may be of particular use to the design of interactive systems. Their work may even enrich activity theory where perceptual matters and the study of tools still call for further effort. Also, the use of multiple bricks on the tabletop calls for careful design in order to reach efficient multi-user concurrent input.

Another perceptual issue related to interactive tools was raised as we studied alternative navigation methods [18]. This work showed that in the plan view mode – when action and perception spaces coincide – there was no difference in the efficiency of fundamentally different navigation principles. In the side view mode – with separate action and perception spaces – there were significant differences. This supports the view that there are advantages to letting action and perception spaces coincide when designing user interfaces [20].

Although simple everyday skills suffice to operate the system, we observed that the need for learning to master advanced functions was not necessarily seen as a problem by the users. Hence, a TUI should offer basic functions that are easy to use alongside advanced functions requiring some training to be operated. That is, the potential trade-off between ease-of-use and learning-by-doing is a relevant design factor.

The BUILD-IT system generally respects body-space since projected light and tangible bricks are hardly intrusive. However, a partially intrusive aspect is the image based tracking of the tangible bricks. Such tracking is not suited to let users move their hands freely across the table. One solution may be found in electromagnetic tracking [34]. Furthermore, the physical height-tools – which were part of our design process – were perceived as intrusive. They actually obstructed users' free hand movements across the table.

Different locking mechanisms between the bricks and the virtual models were implemented, but never explored in empirical studies. However, we believe that the problems of accuracy in model placement and rotation [19] and latency in graphics update [18] will have to be solved prior to the elaboration of alternative locking mechanisms.

The efficient use of two-handed input [38] remains an issue in order to draw effectively from the broad range of everyday manual skills. For instance, the effective use of our hands' coordination and rotation skills – as in the use of a pencil or a compass – is rarely considered in HCI design activities.

This has been a progress report. Much remains to be done. However, tantalising pay-offs of Tangible User Interfaces like BUILD-IT beckon in the distance. These include a better understanding of the activities of planners and designers which uniquely combine behaviour and cognition, the things the hand does and those the mind visualises. They also include commercially more viable applications.

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References

1 Rauterberg, M., Fjeld, M., Krueger, H., Bichsel, M., Leonhardt, U. and Meier, M. (1997) 'BUILD-IT: a computer vision-based interaction technique for a planning tool', in Thimbleby, H., O'Conaill, B. and Thomas, P. (Eds.): *People and Computers XII: Proceedings of HCI'97*, Springer, London, pp.303–314.

2 Fjeld, M., Lauche, K., Bichsel, M., Voorhorst, F., Krueger, H. and Rauterberg, M. (2002) 'Physical and virtual tools: activity theory applied to the design of groupware', in Nardi, B., Redmiles, D.F. (Eds): *Computer Supported Cooperative Work* (CSCW), Vol. 11, Nos. 1–2, pp.153–180.

3 Kaptelinin, V., Nardi, B.A. and Macaulay, C. (1999) 'The activity checklist: a tool for representing the 'space' of context', *Interactions*, Vol. 6, No. 4, pp.27–39.

4 Annett, J. and Stantan, N. (1999) *Task Analysis*, Taylor & Francis.

5 Kirwan, B. and Ainsworth, L. (Eds.) (1992) *A Guide to Task Analysis*, Taylor & Francis.

6 Shepherd, A. (1998) 'HTA as a framework for task analysis', *Ergonomics*, Vol. 41, pp.1537–1552.

7 Bannon, L.J. and Bødker, S. (1991) 'Beyond the interface: encountering artifacts in use', in Carroll, J. (Ed.): *Designing Interaction: Psychology at the Human–Computer Interface*, Cambridge U.P., New York, pp.227–253.

8 Rauterberg, M., Fjeld, M., Krueger, H., Bichsel, M., Leonhardt, U. and Meier, M. (1998) 'BUILD-IT: a planning tool for construction and design (video)', *Summary of Conference on Human Factors in Computing Systems (CHI '98*), ACM, pp.177–178.

9 Hewett, T., Baecker, R., Card, S., Carey, T., Gasen, J., Mantei, M., Perlman, G., Strong, G. and Verplank, W. (1992) *ACM SIGCHI Curricula for Human–Computer Interaction*, Report of the ACM SIGCHI Curriculum Development Group, ACM, p.5. Also available at http://sigchi.org/cdg/cdg2.html.

10 Ullmer, B. and Ishii, H. (2000) 'Emerging frameworks for tangible user interfaces', *IBM Systems Journal*, Vol. 39, Nos. 3/4, IBM, pp.915–931.

11 Fjeld, M., Voorhorst, F., Bichsel, M., Krueger, H. and Rauterberg, M. (2000) 'Navigation methods for an augmented reality system (video)', *Extended Abstracts of Conference on Human Factors in Computing Systems (CHI 2000)*, New York, ACM, pp.8, 9.

12 Fjeld, M., Ironmonger, N., Voorhorst, F., Bichsel, M. and Rauterberg, M. (1999) 'Camera control in a planar, graspable interface', in Hamza, M.H. (Ed.): *Proceedings of the Seventeenth IASTED International Conference Applied Informatics*, ACTA Press, Anaheim/ Calgary/Zurich, pp.242–245.

13 Fjeld, M (2001) *Designing for Tangible Interaction*, PhD Thesis at EHT Zurich. Available at http://e-collection.ethbib.ethz.ch/show?type=diss&nr=14229.

14 Fjeld, M., Bichsel, M. and Rauterberg, M. (1998) 'BUILD-IT: an intuitive design tool based on direct object manipulation', in Wachsmut, I. and Frölich, M. (Eds.): *Gesture and Sign Language in Human–Computer Interaction*, Lecture Notes in Artificial Intelligence, Vol. 1371, Springer-Verlag, Berlin/Heidelberg , pp.297–308.

15 Fjeld, M., Jourdan, F., Bichsel, M. and Rauterberg, M. (1998) 'BUILD-IT: an intuitive simulation tool for multi-expert layout processes', in Engeli, M. and Hrdliczka, V. (Eds.): *Fortschritte in der Simulationstechnik*, vdf Hochschuleverlag AG, Zurich, pp.411–418.

16 Fjeld, M., Lauche, K., Dierssen, S., Bichsel, M. and Rauterberg, M. (1998) 'BUILD-IT: a brick-based integral solution supporting multidisciplinary design tasks', in Sutcliffe, A., Ziegler, J. and Johnson, P. (Eds.): *Designing Effective and Usable Multimedia Systems (IFIP 13.2)*, Kluwer Academic Publishers, Boston, pp.131–142.

17 Fjeld, M., Voorhorst, F., Bichsel, M., Lauche, K., Rauterberg, M. and Krueger, H. (1999) 'Exploring brick-based navigation and composition in an augmented reality', in Gellersen, H-W. (Ed.): *Handheld and Ubiquitous Computing*, Lecture Notes in Computer Science, Vol. 1707, Springer-Verlag, Berlin/Heidelberg, pp.102–116.

18 Fjeld, M., Ironmonger, N., Guttormsen Schär, S. and Krueger, H. (2001) 'Design and evaluation of four AR navigation tools using scene and viewpoint handling', *Proceedings of INTERACT 2001*, Eigth IFIP TC.13 Conference on Human-Computer Interaction, Tokyo (JP), pp.214–223.

19 Fjeld, M., Guttormsen Schär, S., Signorello, D. and Krueger, H. (2002) 'Alternative tools for tangible interaction: a usability evaluation', *Proceedings of the IEEE and ACM International Symposium on Mixed and Augmented Reality (ISMAR 2002)*, pp.157–166.

20 Rauterberg, M. (1995) *Über die Qualifizierung software-ergonomischer Richtlinien*, Ph.D. Thesis, University of Zurich, Zurich.

21 Rauterberg, M. and Steiger, P. (1996) 'Pattern recognition as a key technology for the next generation of user interfaces', *Proceedings IEEE International Conference on Systems, Man and Cybernetics – SMC'96*, Vol. 4, IEEE Press, pp.2805–2810.

22 Eisenberg, M., Mackay, W., Druin, A., Lehman, S. and Resnick, M. (1996) 'Real meets virtual: blending real-world artifacts with computational media', *Proceedings of the CHI'96*, ACM, pp.159–160.

23 Nardi, B. (1996) 'Activity theory and human-computer interaction', in Nardi, B. (Ed.): *Context and Consciousness*, MIT Press, pp.12, 13.

24 Engeli, M., Höger, K., Grote, G., Lauche, K., Seckler, F., Bichsel, M. and Fjeld, M. (2001) 'BUILD-IT Competition', in Engeli, M. (Ed.): *Bits and Spaces: Architecture and Computing for Physical, Virtual, Hybrid Realms*, Birkhäuser Publishers, Basel/Berlin/Boston, pp.26–31.

25 Hasan, H. (2001) 'An overview of techniques for applying activity theory to areas related to information systems', in Hasan, H., Gould, E., Larkin, P. and Vrazalic, L. (Eds.): *Information Systems and Activity Theory*, Vol. 2, Theory and Practice, Wollongong University Press.

26 Arias, E., Eden, H., Fischer, G., Gorman, A. and Scharff, E. (2000) 'Transcending the individual human mind – creating shared understanding through collaborative design', *TOCHI*, Vol. 7, No. 1, ACM, pp.84–113.

27 Fjeld, M. (1998) *BUILD-IT Manual*. Available at http://www.fjeld.ch/pub/manual.pdf.

28 Kiyokawa, K., Billinghurst, M., Hayes, S.E., Gupta, A., Sannohe, Y. and Kato, H. (2002) 'Communication behaviors of co-located users in collaborative ar interfaces', *Proceedings of the IEEE and ACM International Symposium on Mixed and Augmented Reality (ISMAR 2002)*, pp.139–148.

29 Masurat, T. (2001) 'Partizipatives planen von fabrikanlagen am planungstisch build-it', *Tagungsband: Tag der Forschung Informationstechnologie*, TU Clausthal, 25th May 2001.

30 Neuner, M. (2001) 'Team-plattform für die integrierte software-entwicklung', *Informationsdienst Wissenschaft*. Available at http://idw-online.de/public/pmid-42795/zeige_pm.html

31 Aliakseyeu, D. and Martens, J-B. (2001) 'Physical paper as the user interface for an architectural design tool', *Proceedings of INTERACT 2001*, pp.680, 681.

32 Aliakseyeu, D., Martens, J-B., Subramanian, S. and Rauterberg, M. (2002) 'Interaction techniques for navigation through and manipulation of 2D and 3D data', *Proceedings of Eighth Eurographics Workshop on Virtual Environments*, pp.1–10.

33 Steinbach, M. (2000) *An diesem Tisch ist Planung ein Kinderspiel*. Available at http://www.tu-chemnitz.de/spektrum/00-3/tu16.html.

34 Patten, J., Ishii, H. and Pangaro, G. (2001) 'Sensetable: a wireless object tracking platform for tangible user interfaces', *Proceedings of CHI 2001*, ACM, pp.253–260.

35 Ackermann, P. (1996) *Developing Object-Oriented Multimedia Software*, Dpunkt Verlag für Digitale Technologie, Heidelberg.

36 Bateson, G. (1972) *Steps to an ecology of Mind*, Ballantine Books, New York.

37 Gibson, J.J. (1986) *The Ecological Approach to Visual Perception*, L. Erlenbaum, London.

38 Guiard, Y. (1987) 'Asymmetric division of labour in human skilled bimanual action: the kinematic chain as a model', *Journal of Motor Behaviour*, Vol. 19, pp.486–517.