The Complementarity of Tangible and Paper Interfaces in Tabletop Environments for Collaborative Learning

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Résumé

LA TENDANCE ACTUELLE dans le domaine de l'Interaction Homme-Machine est de rapprocher le monde réel du monde digital en créant de nouvelles formes d'ordinateurs, mieux intégrés à leur environnement et disparaissant dans nos maisons, notre mobilier ou même nos vêtements. Tirant parti de notre connaissance intuitive des objets nous entourant au quotidien, de nouvelles interfaces offrent un lien plus direct et naturel entre l'utilisateur et le contenu numérique. Les interfaces tangibles permettent par exemple de contrôler un ordinateur avec des objets physiques. Dans la même optique, les interfaces papier synchronisent les annotations faites à un document imprimé avec sa version électronique. Les propriétés uniques du papier sont également utilisées pour rendre l'utilisation d'applications informatiques plus intuitive.

Dans cette thèse, nous étudions la complémentarité des interfaces tangibles et papier dans le cadre des environnements tabletop. L'objectif est de fournir une solution à deux limitations principales des interfaces tangibles, concernant leur capacité à contrôler des applications complexes (*scalability*), et leur efficacité dans des scénarios pédagogiques, remise en cause par la difficulté d'enseigner des concepts abstraits à l'aide d'objets concrets. Nous proposons comme solution l'utilisation d'un type particulier d'interface papier, des Formulaires Papier Interactifs (FPIs), construits autour de la métaphore du formulaire, en combinaison avec une interface tangible. Nous nous intéressons en particulier au cas des environnements tabletop et introduisons le concept d'Environnement Tangible et Papier (ETaP). Les FPIs résolvent le problème de "scalability" en offrant une palette d'éléments interactifs génériques qui permettent aux ETaPs de contrôler n'importe quelle application, quelque soit sa complexité. Dans un contexte pédagogique, la représentation concrète offerte par les objets physiques est complétée par des représentations plus abstraites affichées sur les FPIs. L'objectif est de faciliter la compréhension des représentations abstraites en les affichant en parallèle aux objets concrets.

Pour valider cette solution basée sur la complémentarité des interfaces tangibles et papier, nous avons implémenté un ETaP, l'environnement Tinker, avec deux enseignants de logistique dans le contexte du système suisse de formation professionnelle. Un modèle réduit d'entrepôt permet aux apprentis d'explorer les concepts théoriques de leur métier dans un contexte pratique et des TinkerSheets (notre implémentation des FPIs) permettent de contrôler une simulation et afficher les résultats. Notre objectif est d'aider les apprentis à comprendre les concepts théoriques présentés en classe. Dix études ont été menées en suivant une méthodologie de type "Design-Based Research", complétées par des études expérimentales analysant plus en détail certaines questions.

Les questions de recherche générales étudiées dans cette thèse concernent les affordances spécifiques des interfaces papier et tangibles des ETaPs. Nous présentons une analyse qui comprend non seulement les aspects liés à la qualité d'utilisation de ces systèmes, mais s'intéresse également à leur impact sur les activités collaboratives et leur potentiel en termes d'intégration de l'environnement dans son contexte. Un modèle descriptif construit autour de trois cercles d'interactions sert de base à cette analyse: individuel (utilisation), groupe (collaboration) et contexte (intégration). Nous avons identifié des règles de design qui permettent de limiter l'impact des interactions moins directes offertent par les FPIs. Du point de vue collaboratif, les observations d'apprentis résolvant des problèmes autour de l'environnement Tinker montrent que les ETaPs bénéficient du mode d'interaction physique offert à la fois par les éléments tangibles et papier. Les études menées avec l'environnement Tinker en classe démontrent finalement le rôle des FPIs qui servent de pont entre les activités traditionelles de l'école et l'utilisation de l'outil interactif.

Du point de vue pédagogique, des questions de recherche spécifiques s'intéressent d'une part au potentiel de l'environnement Tinker pour les apprentis en logistique et, d'autre part, à son appropriation par les enseignants. Nous montrons dans cette thèse que la représentation concrète offerte par le modèle réduit d'entrepôt facilite la compréhension des concepts théorique en réduisant la complexité des activités proposées aux apprentis. Des études contrôlées comparant une interface tangible avec une interface *multitouch* démontrent que les objets physiques améliorent non seulement l'apprentissage mais également la qualité des solutions produites. Nos observations illustrent également le rôle central joué par l'enseignant, qui agit en tant que chef d'orchestre, guide les apprentis au travers des tâches et encourage les activités de reflection en mettant sur pied des sessions de mise en commun. Nous avons également identifié l'importance du design des FPIs qui permet de jouer sur leur double rôle d'interface et de document et facilite leur intégration dans l'écosystème d'une classe.

Mots-clés: *Interfaces Tangibles, Interfaces Papier, Réalité Augmentée, Apprentissage Collaboratif Supporté par Ordinateur, Formation Professionnelle.*

Abstract

THE CURRENT TREND in Human-Computer Interaction aims at bridging the gap between the digital and the real world, exploring novel ways to engage users with computational devices. Computers take new forms that are better integrated into our environment and can be embedded in buildings, furniture or clothes. Novel forms of interfaces take advantage of people's intuitive knowledge of everyday objects to offer more direct and natural interactions. Tangible User Interfaces (TUIs) allow users to interact with digital objects through tangible artifacts, building on their rich physical affordances. Paper User Interfaces (PUIs) add digital capabilities to paper documents, synchronizing for instance their content with their digital counterpart. Unique properties of paper are also used to create engaging and intuitive interfaces to computer applications.

This dissertation is interested in the complementarity of tangible and paper interfaces in tabletop environments. We introduce the concept of Tangible and Paper Environments (TaPEs) where Interactive Paper Forms (IPFs), a particular type of PUIs based on the paper form metaphor, are used as a complementary interface to a TUI. We evaluate the potential of IPFs to overcome two main shortcomings of TUIs, in terms of scalability and pedagogy. The *scalability issue* comes from the limited expressiveness of task-specific physical artifacts, which offer rich physical affordances but limit the complexity of applications that can be controlled by a TUI. The *pedagogy issue* is raised by the lack of consistent evidence regarding the use of physical manipulatives in educational settings, which is one of the main application domain of TUIs. IPFs overcome the scalability issue by offering a set of generic interaction elements that allow TaPEs to cope with applications of any complexity. In a pedagogical setting, IPFs present learners with abstract representation which facilitate understanding by the embodied and concrete representations offered by tangible artifacts.

A TaPE, the Tinker Environment, has been developed with two logistics teachers in the context of the Swiss vocational training system. It consists of a warehouse physical small-scale model (TUI) and TinkerSheets, our implementation of IPFs. It aims at helping apprentices understand theoretical concepts presented at schools. We followed a Design-based Research (DBR) approach: ten studies were conducted during the development of the Tinker Environment in authentic classroom settings. Controlled experiments were conducted to address specific questions.

The general research questions concern the respective affordances of paper and tangible components of TaPEs. The analysis is not limited to usability aspects but also considers their impact on group problem-solving activities and their potential in terms of integration of the system in its context of use. A descriptive model is proposed, built around three interaction circles: individual (usability), group (collaboration) and context (integration). Results identify design guidelines that limit the impact of the less direct interaction modality offered by IPFs, allowing TaPEs to overcome the scalability issue while supporting rich interactions. At the group level, observations of groups of apprentices solving problems around the Tinker Environment show that the consistent physical interaction modality offered by TaPEs naturally supports collaborative interactions. Apprentices tend to take implicit roles based on their location around the system. Regarding the context circle, we observed that carefully designed IPFs play the role of bridges between offline and online activities and contribute to a tight integration of the system in a its context (i.e. a classroom).

The specific research questions address the potential of the Tinker Environment in this pedagogical context and its appropriation by teachers. The observations conducted with the Tinker Environment show that the warehouse small-scale model reduces the complexity of problems and allows apprentices to engage in meaningful problem-solving activities. Controlled experiments comparing a TUI to a mulitouch interface demonstrate that tangible artifacts lead to a higher learning gain and an increased performance in a problem-solving activity. Collaboration quality and perceived playfulness are also improved. The teacher plays a central role in the use of the environment, guiding apprentices through activities and encouraging reflections during debriefing sessions. The design of IPFs, emphasizing either their interface or document nature, has a strong influence on their ability to support teachers. We finally discuss the two-way adaptation process that took place between teachers and the system during the development of the Tinker Environment.

Key words: *Tangible User Interfaces, Paper User Interfaces, Augmented Reality, Tabletop computing, Computer-Supported Collaborative Learning, Vocational training.*

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Contents

Chapter 1

Introduction

THE SHORT HISTORY OF MODERN COMPUTATION, which began in the first half of the 20th century, already underwent two main revolutions. The first digital computing devices, mainframes, had the size of a room, were expensive and used to be shared among many users. Computers became personal in the 1980's with the advent of smaller and cheaper devices. They quickly invaded the desks of office workers and soon made their way to private homes. The second big change happened during the next decade, caused by the development and democratization of internet. The possibility for digital devices to communicate with each other, together with their rapid miniaturization, was recognized by some researchers as the beginning of a novel era for computers, known as Ubiquitous Computing (UbiComp).

As pointed out by [Weiser and Brown, 1997], these three eras illustrate an evolution of the relationship between humans and computers. In the mainframe era a single computer was shared by many users. A more intimate connection took place in the personal computer era, where computers belonged to a single person and stored their data. UbiComp is interested in the capacity of today's digital devices to be everywhere, embedded in our houses, furniture, clothes and their possibility to communicate with each other and provide a constant, unlimited and personalized access to information. The relationship advocated by UbiComp is more diffuse, with people sharing hundreds of computing devices constantly surrounding them.

Widely recognized as the father of this research field, Weiser's vision of *Calm Technology* strongly influenced the early developments in the UbiComp research field [Weiser, 1995]. According to Weiser, if computers are going to surround us all the time, they should better stay out of the way most of the time and only enter our attention scope when necessary. The vision puts a strong emphasis on smart computational devices, able to anticipate users' needs and detect appropriate time to interrupt them.

The ambitious objectives set by Weiser's original vision for *Calm Computing* [Weiser, 1995], in particular in terms of artificial intelligence, led to rather disappointing results. Rogers criticized this approach focusing on smart computers and passive users [Rogers, 2006]. She questioned in particular the willingness of people to live in a world ruled by computers and proposed to shift the focus of UbiComp research from proactive computers to proactive users. The emphasis, she argued, should be on enriching the user experience and reflect on the way UbiComp technologies can be used to achieve this goal. In this new approach, the computer goes back to its original design goal, which is to be a tool to enable and enrich human activities. While the early works in the field of UbiComp fostered passive users surrounded by smart computers reacting to implicit actions, the shift proposed by Rogers emphasizes explicit interactions between humans and computers. Her vision calls for new types of computers, built as an ecology of special purpose resources. The third era of computation would thus correspond to a diversification of devices with different forms and dedicated to particular problems and situations.

1.1 Context and Contributions

This dissertation follows the design philosophy outlined by Rogers. It is about the affordances of novel types of interfaces that go beyond the traditional mouse and keyboard interaction modalities of personal computers. Technologies developed in the field of UbiComp allow computers to take new forms and get closer to the real world, adding computational capabilities to everyday physical objects. More precisely, this dissertation is about Tangible User Interfaces (TUIs) and Paper User Interfaces (PUIs) and poses the question of the their complementarity in tabletop environments.

TUIs allow people to interact with digital content using physical artifacts. Instead of using a mouse to point and click on virtual objects, TUIs make it possible to directly grasp a physical representation of the digital object. Actions on the real objects are captured by the system and translated into actions onto their digital counterparts. These interfaces take advantage of the intuitive knowledge people have of everyday object to create interfaces that are easy to learn and engage users in meaningful interactions. TUIs are often coupled with Augmented Reality techniques that overlay digital information directly on top of real objects. This combination creates immersive environments where input and output are merged onto the same artifacts. The barrier between the digital and the real worlds tends to disappear: users have the impression to directly manipulate the digital data.

PUIs follow an approach similar to TUIs in the sense that they also build on people's knowledge of everyday objects, i.e. paper. The motivation underlying the development of these interfaces is based on the observation that paper, despite widespread computers, is still heavily used in many situations including both professional and personal contexts. Paper has many advantages but also suffers from some limitations compared to digital media. One research path in the field of PUIs tries to add digital capabilities to paper documents while keeping the unique properties of the original material. Another approach, which this dissertation is concerned with, uses paper to control computer applications with the hope that users will benefit from their familiarity with paper documents such as books, notebooks or administrative forms.

This dissertation addresses two main shortcomings of TUIs, which we refer to as the scalability and the pedagogy issues. The scalability issue comes from the limited expressiveness of task-specific physical artifacts, which offer rich physical affordances but limit the complexity of applications that can be controlled by a TUI. A small-scale model of a bridge, for instance, has a specific meaning and should not be used to represent anything else than a bridge. The pedagogical issue is concerned with the lack of consistent evidence regarding the use of physical manipulatives in educational settings, which is one of the main application domain of TUIs. We address in particular the case of tabletop environments and propose the concept of Tangible and Paper Environments (TaPEs) which offer a mixed tangible and paper interaction modality. Interactive Paper Forms (IPFs), a particular type of PUI based on the paper form metaphor, are used as a complementary interface to a TUI.

IPFs overcome the scalability issue by offering a set of generic interaction elements that allow TaPEs to cope with applications of arbitrary complexity while offering a rich user experience thanks to task-specific physical artifacts. We introduce a descriptive model for TaPEs that relies on three interaction circles: individual, group and context. The first objective of this dissertation is to assess the complementarity of tangible and paper components of TaPEs. Three general research questions consider the respective affordances of these two interaction modalities at the three levels of interaction defined by our model. In the individual circle, tangible artifacts are expected to play a central role. At the group level, our hypothesis is that the physical nature of tangible and paper interfaces provides a consistent interaction modality that supports collaborative activities. Paper is finally expected to play a crucial role at the context level for the integration of the environment in its wider context of use. We consider in particular the potential of IPFs to be integrated into existing paper documents and support seamless transitions between online and offline activities.

The second central objective of this dissertation is to assess the potential of TaPEs in educational settings. The concrete and embodied representation of a problem given by tangible artifacts tends to keep learners in a concrete mode of reasoning. Building on the work on Multiple External Representations (MERs), our hypothesis is that IPFs can be used to address the pedagogical limitation of TUIs by providing learners with representations at a higher level of abstraction. Abstract representations are easier to understand because they can be related to the concrete representation given by tangible artifacts.

These assumptions have been tested with apprentices in logistics, in the context of the Swiss vocational training system. The particularity of this system is to be mostly organized in a dual way: apprentices go to school one day per week and are employed in a company the rest of the time. A field study conducted in schools and companies identified an issue faced by apprentices in logistics, which we refer to as the abstraction gap: schools present concepts in a too theoretical way and apprentices often do not have the opportunity to apply them at their workplace. We propose a pedagogical approach based on the specific properties of TaPEs. A warehouse small-scale tangible model (TUI) offers a concrete representation that lowers the difficulty for apprentices to engage in meaningful problem-solving activities while IPFs display information at a higher level of abstraction. We co-developed a TaPE, the Tinker Environment, with two logistics teachers. The system has been used on a regular basis in several professional schools. Three specific research questions are raised. The first one concerns the potential of a small-scale model to overcome the abstraction gap. The second one addresses the potential of the pedagogical approach we propose to support a smooth progression towards abstract representations. The third and last question is interested in the appropriation process of the Tinker Environment by teachers.

1.2 Thesis plan

Chapters 2 and 3 review relevant work in the fields of TUIs and PUIs respectively. Chapter2 identifies two shortcomings of TUIs in terms of scalability and their use in pedagogical settings.

The concept of Tangible and Paper Environment (TaPE) is introduced in Chapter 4. We propose a model based on three circles of interaction: individual, group and context. The three general research questions addressed by this dissertation are finally described together with the research method we followed, Design-based Research (DBR).

The context where this work took place, together with the specific research questions addressed in this dissertation are presented in Chapter 5. It describes in particular the apprenticeship in logistics through the field study that led to the identification of the abstraction gap.

The Tinker Environment is presented in Chapter 6. It includes descriptions of two tabletop environments (TinkerTable and TinkerLamp), the warehouse small-scale model (TUI), our implementation of IPFs (TinkerSheets), the general architecture of the software framework as well as the simulation developed for the apprentices in logistics.

Chapter 7 reports ten studies conducted with the Tinker Environment in authentic classroom settings. They are organized in four chronological phases that represent key milestones in the development of the environment with logistics teachers. Results are provided for each individual study and a short discussion concludes each phase.

The results of the ten studies are gathered in Chapter 8 to provide an answer to the six research questions addressed by this dissertation, which is finally concluded by Chapter 9.

Chapter 2

Tangible User Interfaces

In our daily life, we encounter numerous objects which have many different forms and functions. Over time, we have learnt to recognize some specific features in the shape of these objects that inform us about their purpose and the way we can use them. Take for example the water boiler shown on Fig. 2.1. I use it every morning to prepare a coffee, following a very simple procedure: open the top cover, poor water in it, place the boiler on its base and push a button to start heating the water and wait until it stops. A closer look at this object allows us to see that these actions are culturally guided by its shape. There is a slit on the top cover which fits several fingers: its shape shows that it opens towards the back and indicates that the hand should come from the back of the device. This avoids that the user's arm ends up over the bottleneck where hot steam is passing when water boils. While it would be possible to carry it with two hands placed around its body, the large handle on the side invites us to grasp it with a single hand, which is both more practical and safer since the central part becomes hot when water boils. Finally, the start button is flat, relatively large and situated at the bottom of the device which naturally tells us that it is activated by pushing rather than lifting it.

The term *affordance* has been proposed by Gibson [Gibson, 1977] to describe the actionable properties of objects. Affordances refer to relationships between natural properties of physical objects and a specific actor (animal or human being) which, Gibson argues, exist independently of their perception by the actor. The concept was reused in the design literature by Norman [Norman, 1988] as a way to convey information about possible actions to users. The important concepts in this later use of the term are *perceived affordances*, actionable properties of objects that are recognized as such by users. These are often based on a mix of natural and cultural clues. The shape of a door handle, for instance, affords grasping but we also know that it should be pushed downwards because of the previous experiences we have had with doors.

In their seminal paper *Tangible Bits*, Ishii and Ullmer [Ishii and Ullmer, 1997] introduced the term Tangible User Interface (TUI) to refer to interfaces based on the use of physical objects. These interfaces offer a close coupling between the digital and the real world, allowing users to manipulate digital information in the same way they are used to manipulate physical objects. TUIs rely on the rich physical affordances of objects to develop systems that are intuitive and thus easy to learn for novices.

Figure 2.1: The water boiler I use to prepare my morning's coffee and its perceived affordances: the slit on the top cover which fits several fingers, the large handle on the side that invites people to carry it with a single hand rather than grasping the potentially hot main body and the low position of the start button which affords pushing.

A prototype application of these concepts is Tangible Geospace, running on the metaDESK [Ishii and Ullmer, 1997], a back-projected interactive surface. Users manipulate a map of the MIT campus using small-scale models of some of its buildings. Whenever a building is placed on the surface, the map is aligned with it and its orientation can be controlled by rotating the object. Users zoom by placing a second object on the map and by moving them closer or farther away from each other. Other physical tools are available, like the activeLENS which is an LCD screen displaying a 3D view of the campus updated according to its position compared to the map currently displayed.

The idea of *tangible manipulation* was actually pioneered by the work of Wellner [Wellner, 1991]. While the prevailing approach to user interfaces was based on the desktop metaphor, making the computer desktop look like a real desk, Wellner proposed the opposite approach: make the real desk capable of computing things like office software suites. He developed the DigitalDESK, a standard office desk augmented with digital capabilities. A camera and a projector located above it merged digital content into real paper documents and allowed users to interact with digital information by pointing at it with their fingers.

Fitzmaurice paved the way towards TUIs with his work on *Graspable User In-*

terfaces [Fitzmaurice et al., 1995, Fitzmaurice and Buxton, 1997], based on physical tokens that can be attached to digital content to manipulate it. He identified a series of advantages that can be obtained from the use of physical tokens. Their support of two-handed interactions and parallel input improves the expressiveness of the communication with the computer system. They also use more specialized, context-sensitive input devices and take advantage of our natural spatial reasoning skills. A set of short experiments pointed out important properties of these interfaces. They support a high degree of parallelism: users often perform several tasks at the same time, which is possible thanks to two-handed input. The gestural vocabulary tends to be rich, including crossed arms, pick or slide movements as well as the possibility to move multiple bricks at the same time using the hand as a bulldozer. A crucial aspect is the tactile feedback which allows users to finish an action while visually attending to other tasks.

2.1 Direct Manipulation

TUIs share many of the underlying principles of current desktop computers Graphical User Interfaces (GUIs), commonly referred to as WIMP (Windows - Icons - Menus - Pointing device) interfaces. The introduction of these interfaces at the beginning of the 1980's revolutionized the entire paradigm for Human-Computer Interaction (HCI) from dialogue to manipulation [Frohlich, 1997]. The prevailing way for interacting with a computer at that time was through command-line interfaces. Users had to type commands in a terminal, the computer would perform the requested operations and give feedback in a text form. GUIs changed this conversation-based interaction pattern by allowing users to perform *direct actions* on digital objects, using physical movements mediated by a pointing device (i.e. a mouse). Instead of issuing commands to modify the state of an object, for instance moving a file, users could drag and drop a visual representation of the file from one folder to another. Another central concept of GUIs is the *visibility* of the system state, given by rich visual representations of the objects. This is not the case with command-line interfaces where each piece of information has to be explicitly required by issuing a command.

The term Direct Manipulation (DM) was coined by [Shneiderman, 1983] to describe this type of interfaces based on direct action and visibility of digital objects. He defined three basic principles of DM interfaces:

- Continuous representation of the objects and actions of interest;
- Physical actions or presses of labeled buttons instead of complex syntax;
- Rapid incremental reversible operations whose effect on the object of interest are immediately visible.

A list of potential benefits of these interfaces have been proposed by [Shneiderman, 1997]:

- Novices can learn basic functionality quickly, usually through a demonstration by a more experienced user;
- Experts can work rapidly to carry out a wide range of tasks, even defining new functions and features;

- Knowledgeable intermittent users can retain operational concepts; error messages are rarely needed;
- Users can immediately see if their actions are furthering their goals, and, if the actions are counterproductive, they can simply change the direction of their activity;
- Users experience less anxiety because the system is comprehensible and because actions can be reversed so easily;
- Users gain confidence and mastery because they are the initiators of action, they feel in control, and the system responses are predictable.

DM interfaces are however not perfect and a range of drawbacks have been identified in the literature. Actions within these interfaces are usually performed by first selecting an object (point and click) and then issuing the command through gestures such as pointing, circling or dragging. Buxton argues that the selection of the target of the action, which he calls *by demonstration*, is inappropriate for most of the applications [Buxton, 1993]. He argues that DM interfaces lack a way of selecting objects *by description*, which allows users to apply the same action to a large range of objects selected through a description of their properties. He takes the example of a digital gate-logic design program. If one wants to switch all the AND gates that directly follow an OR gate to NAND gates, a typical DM interface would require the user to click on each gate independently and issue the command.

Another criticism often stated against DM interfaces concerns the limitations of the desktop metaphor. A good example is the trash can which is a metaphor of the real office trash and allows users to delete files by dragging and dropping them on it, but is also used on Macintosh computers to eject external storage devices. According to [Gentner and Nielsen, 1996], metaphors may fail because of a mismatch between the number of features they present compared to the target domain, or a mismatch between similar features that work in entirely different ways.

2.1.1 Elements of Direct Manipulation interfaces

Object of Interest and DM tools

Applications usually have a central area where most of the interactions take place. This area represents the document (the digital object) that users are currently working with, and is known as the Object of Interest (OoI) [Hutchins et al., 1985]. The OoI is specific to each application and can be for example a text, a drawing, a set of cells in a spreadsheet, a HTML document or a list of files and folders in a file system explorer. Possible actions on the OoI also differ from one application to another but are usually easy to discover: they use perceived affordances by adding visible elements to the OoI (e.g. handles in a graphics software), and use real-world metaphors to guide users. For instance, the size of a column in a spreadsheet is changed by clicking on its border and dragging it. The same kind of action is performed to select part of a text: place the mouse cursor at the beginning of the region to select, then click and drag the cursor to the end of this region. Text can also be moved with another *drag&drop* action, similar to the action of grasping an object and moving it to a new location.

Direct, physical manipulations of the OoI are usually limited to actions such as translate, rotate or resize. In the same way we use tools in many real world situations, a set of specific DM tools are usually available in GUIs to perform different actions on the OoI. Good examples are graphics applications which typically provide a large set of tools such as pencils, paintbrushes or an eraser. They are usually presented in a palette displayed next to the OoI. Users first have to select them by clicking on their icon in the palette before directly applying them to the OoI.

Peripheral interface elements

While the OoI and DM tools provide intuitive and rich interactions by following DM principles, they are not sufficient to build a fully functional application. Users want to be able to do more than manipulating objects, like adding new shapes to a drawing or change its color, set border size of cells in a spreadsheet or modify the appearance of a text. The tools themselves can often be configured, like for example the size of the paintbrush tool in a graphics software. Other important actions include adding or removing visual aids, open and close documents or change global properties of a document such as its size (e.g. A4, letter, . . .). This is the reason why secondary interface elements like menus and toolbars have been added to GUIs. It is also interesting to mention *property pages*, which were part of the first commercially available GUI, the Star User Interface [Smith et al., 1982]. They were an early implementation of contextual menus: a special key on the keyboard opened the property page of any selected object and would give users instant access to all the relevant properties of this object.

The purpose of these elements is to let users control hidden and otherwise inaccessible properties of the OoI, as well as other parameters like document management operations (e.g. open/close) and application properties (e.g. window size). Palettes often give access to a set of tools that can be used to modify the OoI using DM principles (e.g. pencil, paintbrush or shape creation tools in a drawing application). Toolbars are primarily used to give direct access to most often used actions (e.g. fonts properties in a text editor or cells background color in a spreadsheet application). Menus are used to access the full set of functionalities and application properties. Some menu items open pop-up windows that group a set of related properties, similar to Xerox Star's property pages.

2.1.2 Analysis of Direct Manipulation interfaces

Semantic vs syntactic knowledge

Advantages of DM over command-line interfaces have been explained by the fact that they are based on semantic knowledge rather than syntactic knowledge [Shneiderman, 1983]. Syntactic knowledge is arbitrary, often acquired by rote memorization, is easily forgotten and usually system dependent. On the contrary, semantic knowledge is largely system independent, is acquired through general explanation, analogy and examples, is easily anchored in familiar concepts and is therefore stable in memory. Early implementations of GUIs used to push this idea quite far by relying strongly on metaphors. They mimicked an office desktop with icons representing typical elements like a printer, files, folders or a trash can. The goal was to allow users to apply their knowledge of the real object to the digital environment. To delete a file, users could simply drag and drop the icon of the file on top of the trash can icon, similar to the action they would perform in the real world. As already stated, the use of a very direct metaphor tends to confuse users who expect the computer to work exactly in the same way as their physical environment, which is not always the case. As a result, the representation of the office desktop in GUIs became less literal over time.

Gulf of execution and gulf of interpretation

Hutchins, Hollan and Norman [Hutchins et al., 1985] provide a cognitive account of DM interfaces. Their assumption is that the feeling of directness is the result of the commitment of fewer cognitive resources, described along two dimensions: the distance *between one's thoughts and the physical requirements of the system under use*, and engagement, *the feeling that one is directly manipulating the objects of interest*. They represent the distance between users' intentions and the computer system through the *gulf of execution* and the *gulf of evaluation*. The gulf of execution represents the distance between users' intentions and their execution by the computer: intentions have to be translated into an interface language and communicated to the computer. The gulf of evaluation corresponds to the way back, i.e. the distance between the feedback given by the computer after execution and its interpretation by users. Hutchins et al. defined two types of distances to refer to the gulf between users' intention and computer systems:

Semantic distance depicts the relationship between users' goals and the meaning of expressions in the interface language;

Articulatory distance stands for the relationship between these expressions and their physical form.

DM interfaces reduce the semantic distance by providing users with high-level languages which directly express typical structures of problem domain. The problem of using high-level languages is the loss of generality which limits their use to specific domains. The same conflict arises on the output side where the semantic distance can be reduced by the use of specialized visual representations which display semantic concepts directly but lack generality. The articulatory distance can be reduced by implementing interfaces based on physical movements that mimic the actions that are performed. This is the case of DM interfaces which take advantage of the rich spatio-mimetic properties of pointing devices.

The Instrumental Interaction Model

The Instrumental Interaction model developed by [Beaudouin-Lafon, 2000] defines a design space for new interaction techniques and proposes a set of properties to simplify their comparison. It is primarily concerned with GUIs and covers existing interaction techniques such as Windows-Icon-Menu-Pointing device (WIMP) interfaces, but can also be applied to the analysis of TUIs.

The model is based on the observation that WIMP interfaces do not respect the principles of DM because they rely on peripheral interface elements such as menus, toolbars or dialog boxes. In the same way we use tools to interact with objects of interest in the real-world (e.g. we write with a pencil but are ultimately interested in the document), users do not act directly on the digital object of interest. They use these peripheral or secondary interface elements which, as argued by Beaudouin-Lafon, provide only a limited sense of engagement. Instrumental Interaction captures this situation through three main concepts:

Domain objects are the main elements of an interface on which the users' attention is focused. Domain objects have *attributes* that describe their characteristics, like for example the position, size and orientation of a graphical element in a drawing application. Users interact with domain objects by manipulating them as a whole (e.g. translate, rotate, delete) or by editing their attributes.

Interaction instruments are mediators between users and domain objects. Actions of users on instruments are translated into commands that affect targeted domain objects. Instruments have *reactions*, which help the users control their actions on the instrument, and provide *feedback* when the action is applied to the domain objects. Before being used, instruments first have to be activated by users. The activation can either be *spatial*, if users have to move the mouse in a particular area on the screen (e.g. scrollbars), or *temporal*, when a certain sequence of actions or a gesture have to be performed (e.g. rectangle selection tool: press the mouse button, move to another location and release the button). Spatial activation takes space on the screen since the instrument has to be visible (e.g. a toolbar or a palette) and may split the attention of users who have to move towards it. Temporal activation is slower and less direct since it requires explicit actions to be performed.

Meta instruments are groups of commands embedded into an interaction instrument, like for example menus in WIMP interfaces. It is based on the concept of *reification*, often used in GUIs to group a set of properties or attributes into an object. Styles in text editors are for example a reification of several text attributes. Meta instruments are useful to organize instruments, such as palettes that can be freely moved around the workspace. In this case, meta-instruments temporarily become domain objects because they are at the center of the attention of users who interact with them directly.

The model also provides three properties of instruments that are useful to compare different interfaces and evaluate them.

The *degree of indirection* is related to the temporal and spatial types of activations of an instrument and is a measure of the offset along these two dimensions. The *temporal offset* is defined as *"the time difference between the physical action on the instrument and the response of the object"* ([Beaudouin-Lafon, 2000], p. 5). Scrollbars offer for example a real-time response to users actions, but dialog boxes apply the changes made to available properties only when a confirmation button is pressed.

The *degree of integration* is a measure of the ratio between the number of Degrees of Freedom (DOFs) offered by an instrument compared to the number of DOFs captured by the input device. Scrollbars have for example a degree of integration of 1/2 because the instrument has 1 DOF but the input device, a mouse in this case, has 2 DOFs.

	Indirection	Integration	Compatibility
Menus	- -	+/-	- -
Toolbars	-	+	+
Dialog boxes	- -	+/-	-
Property boxes	+	+/-	-
Window titles	+ +	+	+
Drag & drop	+ +	+ +	+ +

Table 2.1: Comparison of main WIMP interaction elements using properties defined by the Instrumental Interaction model.

The *degree of compatibility* measures the similarity between users' physical actions on an instrument and their impact on the targeted object. DM techniques such as drag-and-drop have a high degree of compatibility since the object follows directly the movement of the mouse pointer, but entering numerical values in a dialog box to set a property such as the size of an object has a low degree of compatibility because the nature of the input and the output is different.

2.1.3 The scalability issue in WIMP interfaces

The main purpose of a user interface is to make the functionalities of a software application available to users by offering both input and output mechanisms. The question of the mapping between software functions and interface elements is challenging because user interfaces have to be able to cope with applications of arbitrary complexity, ranging from a few to hundreds of parameters and data items that must be made available to users. The way TUIs handle this issue, which we will refer to as the scalability issue, is central to this dissertation and will guide the review of relevant work in the next section. We now look at the solution developed by WIMP interfaces as a basis for discussion.

Table 2.1 shows a selection of some of the interface elements of WIMP interfaces, described in terms of their degrees of indirection, integration and compatibility, as reported in [Beaudouin-Lafon, 2000]. Peripheral interface elements such as menus, palettes or toolbars offer higher degrees of indirection than DM interactions based on *drag&drop* actions. This analysis illustrates the trade-off that is made between scalability and Direct Manipulation.

The peripheral interface elements surrounding the Object of Interest (OoI) extend the functionalities of an application by relaxing some constraints of the DM principles, mainly in terms of visibility and directness of interaction. They allow WIMP interfaces to handle software of any size and complexity. Relatively simple applications rely mostly on OoIs and DM tools while more complex applications require the use of peripheral interface elements to handle a larger number of functionalities (Figure 2.2). The complexity of an application is defined here as the number of parameters and options that can be set by users and is thus not related to the complexity of the domain it addresses. For instance, a difficult game with a limited set of possible user actions is much less complex than a word processing application with its hundreds of formatting and customization options.

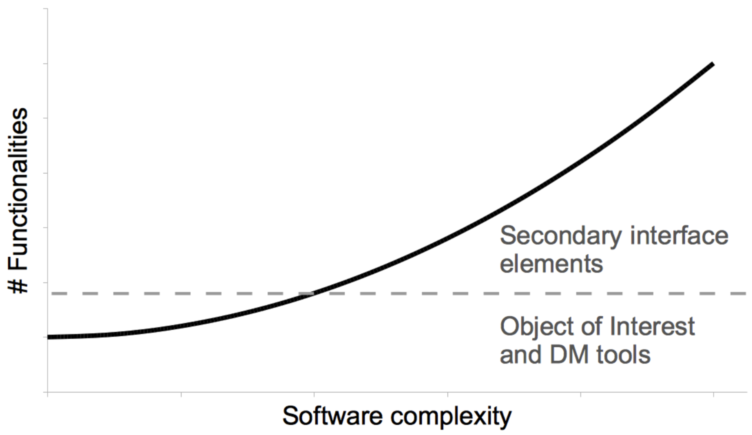


Figure 2.2: This chart shows how the number of functionalities that have to be mapped onto an interface augments with the complexity of software applications. WIMP interfaces rely on two types of interface elements: the OoI and DM tools for rich and direct manipulations on central aspects of the application, and secondary interface elements which allow the interface to handle an arbitrary number of functionalities.

2.2 Representative work

The discussion on DM interfaces directly applies to TUIs which extended these main concepts by providing users with a physical instantiation of Objects of Interest. While interactions with desktop computers are still mediated by a mouse which implies a certain distance between the users and the objects with which they interact, TUIs go a step further by offering *real* Direct Manipulation of the digital objects through physical artifacts. From the point of view of the user, real objects and their digital counterparts are the same: physical actions, which are guided by the shape of the artifacts are applied directly to the objects. Moreover, TUIs offer the possibility to merge input and output: results of actions are immediately available at the place where they take place. This is not the case with DM interfaces: input is done through a pointing device or a keyboard and output is displayed on a screen. TUIs reduce the articulatory distance by relying on rich physical interactions that mimic the actions performed on digital objects. Regarding the semantic distance, we can distinguish two types of TUIs which differ in terms of the similarity of their appearance with the digital objects they represent. The semantic distance is lower if the tangible representation of an object is literal (e.g. a small-scale model of a bridge) compared to more symbolic representations (e.g. raw wooden blocks).

Regarding the mapping of software functionalities onto the interface elements, most of the systems developed in the field of TUIs focused on exploring novel interaction techniques and did not explicitly address this question. As illustrated by the systems presented below, elements of TUIs typically correspond to the OoI or DM tools. Since most of the systems developed so far have been done in a research context, real-world applications were not the focus of these previous works. The question of handling complex applications has thus not been raised.

We organize the review of relevant work in the field of TUIs according to the three classes of systems proposed by [Ullmer et al., 2005]: *constructive assembly* systems, *Token+constraint* systems and *interactive surfaces*. A short discussion follows the description of systems within each class and addresses the mapping between applications functionalities and the TUIs. We do not consider the actual complexity of the applications developed for each of the systems but rather try to estimate the required number of functionalities of a real-world application. The objective is to assess the quality of the match between the actions made available by the interface and the flexibility users would expect from such an application in a real-world scenario. We define a real-world application as a situation where a system is used for a meaningful purpose (e.g. workers solving a problem or children playing), in an authentic setting and on a regular basis. It contrasts with typical evaluations of systems developed in research projects, often conducted in laboratory settings with randomly selected participants who interact with the system for a limited amount of time in an imaginary scenario.

Figure 2.3: Pictures of ActiveCube [Watanabe et al., 2004]. Top: the physical cubes used for the assembly of 3D models. Bottom: a model of a space shuttle detected and displayed on an attached computer.

2.2.1 Constructive assembly systems

Constructive assembly systems are usually based on modular elements which can be assembled together to trigger some events or create 3D models.

ActiveCube [Watanabe et al., 2004] is a tangible interface that supports the construction of augmented 3D models through the assembly of physical cubes. A

Figure 2.4: Two examples of Navigational blocks [Camarata et al., 2002], a constructive assembly system for the retrieval of historical stories in a tourist spot. Information is queried by arranging blocks on an interactive surface: each face contains a written description of the type of information it queries.

microprocessor is embedded in each cube, providing it with a unique ID and communication capabilities. This allows a computer connected to the model through a special cube to detect the shape of the model, recreate it digitally and send information to cubes (Figure 2.3). Some cubes offer specific functionalities: a *gyroscopic sensor* captures the 3D orientation of the model, a LED matrix displays digits, and a fan implements mechanical rotation and can be used to simulate a plane propeller.

The navigational blocks system [Camarata et al., 2002] also consists of similar components, but unlike ActiveCube each block has a unique meaning. Wooden cubes facilitate the retrieval of historical stories in a tourist spot. They allow visitors to explore information available about a particular topic. Each face of a navigational block has a title that indicates which kind of information is attached to it (Figure 2.4). Placing a block on an interactive surface displays a virtual world on a nearby screen. Users navigate through the world and discover information about the chosen topic by moving and rotating the block. Blocks can be associated to narrow the type of topic a visitor wants to access. An interesting aspect of the system is that it provides haptic feedback: blocks either attract or repel one another to indicate whether the topics situated on each block can be associated or not.

SystemBlocks [Zuckerman and Resnick, 2003] aim at teaching dynamic systems to children (Figure 2.5). Compared to ActiveCube and Navigational blocks, it does not need to be attached to an external display and can be used independently: the electronic blocks that compose the system provide both input and output modalities. Moreover, each block implements a specific function: there are for example discrete senders, which send the number one when a button placed on their face is pressed, multipliers, subtractors or accumulators. Dynamic systems are created by attaching blocks together using electrical wires. Special blocks provide feedback through different representation types including digits, graphics and sound.

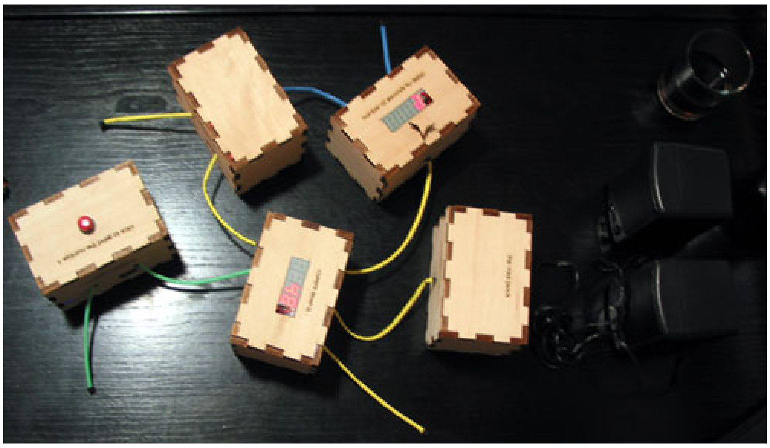


Figure 2.5: SystemBlocks [Zuckerman and Resnick, 2003], a constructive assembly system used to teach dynamic systems to children.

Another example of a self-contained constructive assembly system is Topobo [Raffle et al., 2004], a 3D constructive assembly system targeted towards children and adolescents. Compared to the previous systems, Topobo has the particularity to include components with different physical shapes. Passive and active components are assembled together to create 3D objects, for instance skeletons of animals (Figure 2.6). Active elements have a kinetic memory, which allows them to record movements and replay them.

Mapping between expected features and proposed interfaces

In the four systems presented in this section, the OoI is the result of the assembly of individual building blocks. The interfaces proposed for these applications consist of a one-to-one mapping between these blocks and interface elements: cubes for Active Cube [Watanabe et al., 2004] and Navigational Blocks [Camarata et al., 2002], electronic blocks for SystemBlocks [Zuckerman and Resnick, 2003] and a set of both passive and active components with different shapes in the case of Topobo [Raffle et al., 2004]. These elements represent the OoI. The range of possibilities is given by their physical affordances and no DM tools nor secondary interface elements are used in these examples.

The mapping between the functionalities that we would typically expect from the applications implemented by these systems and the TUIs they propose is well adapted. A limited set of building blocks provide users with a wide variety of possible constructions. The level of complexity of these applications is low and is thus adapted to the tangible interfaces proposed in this section. In the case of Topobo for instance, the possible actions are limited to attaching components together and recording movements but correspond to the expectations of users regarding the type of activities it proposes. The applications have a specific purpose which is fully implemented by the TUIs presented and could be used in real-world settings.

Figure 2.6: A creature created with Topobo [Raffle et al., 2004], made of passive and active components. The kinetic memory of active elements have a kinetic memory, that allows children them to record movements and replay them.

2.2.2 Token+constraint systems

Token+constraint systems take advantage of physical constraints of tangible objects to *guide* the interaction. The term has been introduced by [Ullmer, 2002], who describes TUIs in terms of two concepts: *tokens* act as containers and parameters representing digital information while *constraints* structure the way tokens can be arranged or associated.

The marble answering machine [Moggridge, 2006] developed by Durrell Bishop during his Master thesis at the Royal College of Art in 1992 is an early example of such a system. It is a prototype of a phone answering machine exploring the use of everyday objects to interact with digital data. Voice messages are represented by marbles (tokens) which pop out of the machine when they are recorded (Figure 2.7). The amount of visible marbles gives an immediate feedback on the number of messages that have been received. Users interact with the machine by grasping marbles and dropping them in different places (constraints) allowing them to hear a message, call back or erase it. The association between data and physical tokens is only temporary and lasts until the message is deleted. There is no visual similarity between a marble and the data it is associated with.

Another example has been proposed by [Blackwell et al., 2004] to support collaborative information retrieval. Participants arrange relevant pieces of information represented by *statement tokens* on physical racks (constraints) connected to a computer (Figure 2.8). The arrangement of tokens, detected using RFID technology, defines queries which results are displayed on a nearby screen. Information related to a token can be obtained through a specific reader and is used to create new

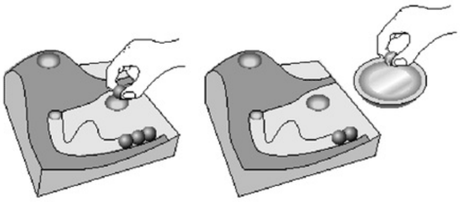


Figure 2.7: The Marble Answering Machine [Moggridge, 2006]: marbles act as a physical representation of voice messages. Each time a message is left on the device, a new marble pops out of the device. Users handle messages by placing marbles on predefined locations to hear them or call back. Messages are erased by placing the marble back in the pool of blank marbles at the top of the machine.

Figure 2.8: The collaborative information retrieval system proposed by [Blackwell et al., 2004]. Statement tokens are arranged on physical racks to query information displayed on a computer screen.

tokens and refine the query. Compared to the Marble Answering Machine, there are two types of tokens used in this system: initial statement tokens with a fixed associated data or meaning, identified with a written label, and custom tokens that are created by the users which only have temporary meaning.

Senseboard [Jacob et al., 2002] is a platform which allows groups of users to organize information pieces on a grid (constraint). This system has been applied to the task that consists in organizing conference papers into sessions and scheduling them (Figure 2.9). Each paper is represented by a magnetic puck that is be placed on a vertical sensing surface divided in cells representing time slots. The association between a paper and a puck is fixed but can only be identified when the puck is placed on the interactive board: the information about the paper is projected directly on top of the puck. SenseBoard introduced the use of tangible tokens with different sizes and shapes as commands, like for example a *view details* puck which

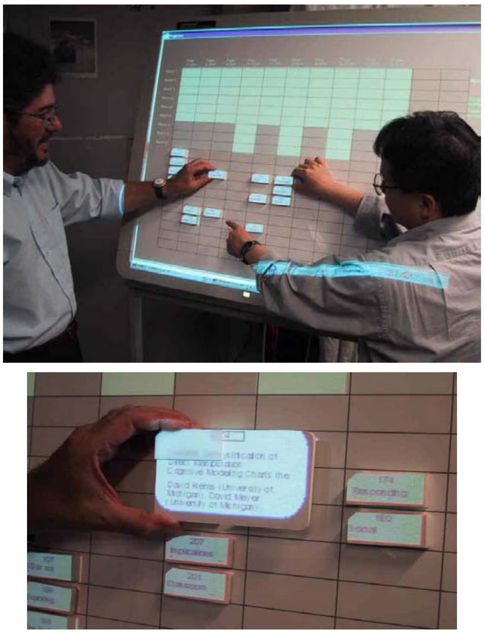


Figure 2.9: Top: a picture of Senseboard [Jacob et al., 2002], a collaborative platform to arrange information on a grid. In this example, two users use it to organize conference papers into sessions. Bottom: the *view details* command puck, which displays additional information about the paper on which it is placed.

displays additional information about a paper when placed on its puck (Figure 2.9) or the *puck* to place several pucks into a single one. Additional digital information is projected on the grid to inform users about potential problems like conflicts when papers about similar topics are placed in parallel sessions. An *export* command finally converts the result in a file compatible with other software.

Mediablocks [Ullmer et al., 1998] illustrates the use of tangible artifacts as temporary containers for digital information. Small wooden blocks are used as *phicons* (physical icons [Ullmer and Ishii, 1997]) to transfer data among different devices (Figure 2.10). The system includes a set of specific physical tools to manipulate media elements. A *media browser* displays the content of a mediaBlock placed on a slot. Users navigate through the content thanks to a physical wheel placed in front of the browser. The content of a block can be modified with the *media sequencer*. It integrates a set of physical constraints (racks, stacks, chutes and pads) used for instance to copy content from one mediaBlock to another one or to combine the content of several blocks (Figure 2.10).

DataTiles [Rekimoto et al., 2001] mix Graphical and Tangible User Interfaces aspects. Users interact with tagged transparent tiles that are augmented when placed on a tray (flat panel display). Tiles are arrange manually and a pen or a mouse allow users to interact with digital content, as they would do in a traditional GUI system (Figure 2.11). Different kinds of tiles are available: application tiles are

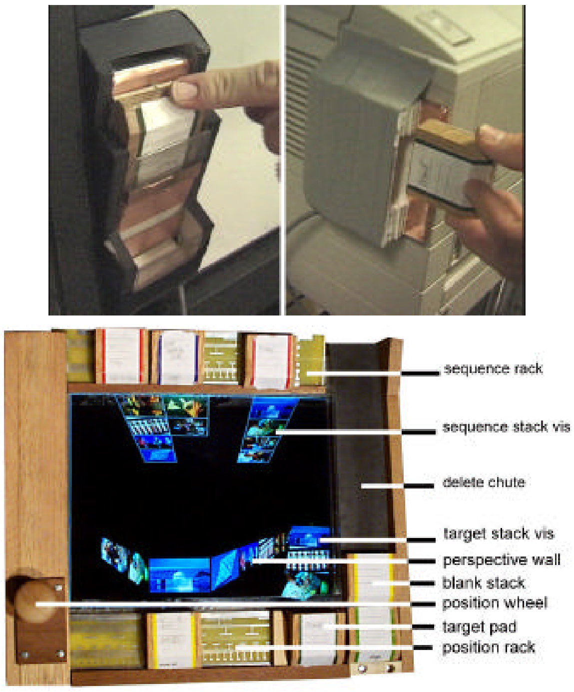


Figure 2.10: Examples of Mediablocks [Ullmer et al., 1998], temporary tangible containers for digital information. Top: blocks used to transfer data among devices (a digital whiteboard and a printer). Bottom: the *media sequence* which is used to modify the content of a block.

bound to a specific function activated when the tile is placed on the tray, portal tiles give access to physical objects like printers, parameter tiles to control other tiles (e.g. time wheel), container tiles record the content of other tiles and remote tiles connect different trays. Some tiles use physical constraints to facilitate the use of their function: the time wheel parameter tile, for example, has an engraved circle which guides pen input (Figure 2.11).

Mapping between expected features and proposed interfaces

As in the case of the constructive assembly systems, the OoI of applications presented in this section are mapped in a one-to-one way onto individual elements of the interface. The OoI usually corresponds to tokens, such as the messages in the Marble Answering Machine [Moggridge, 2006] represented by physical marbles, the papers that take the form of a puck on Senseboard [Jacob et al., 2002] and digital data in Mediablocks [Ullmer et al., 1998] attached to tangible blocks. Several examples of DM are also found, such as the specific tokens used to issue commands on Senseboard (e.g. copy, display additional information, . . .). Constraints can also be considered as DM tools in some cases where actions are triggered by placing a token on top of them. Examples include the Marble Answering Machine, where commands are issued by placing marbles at different locations on the machine, or the *media sequencer* developed for MediaBlocks. Unlike WIMP interfaces where

Figure 2.11: Several DataTiles [Rekimoto et al., 2001] arranged on a tray. The two illuminated circles are engraved in the tile to facilitate pen-based interactions.

actions are performed by first selecting a tool before applying it to the OoI, in these cases the OoI itself is moved by the users and placed on the tool.

Even though the TUIs presented in this section are relatively limited in terms of possible actions offered to users, most of them implement the functionalities that would typically be expected in a real-world situation. In the case of the Marble Answering Machine for instance, all the basic functionalities of such a machine are offered by the proposed interface, with the advantage of the simplicity offered by the physical manipulation of messages. The quality of the mapping for systems such as Senseboard or DataTiles depends on the type of application they propose. The reason is that these environments have a less specific purpose than other previous examples and may thus be used for applications with a higher complexity, that require a larger amount of interface elements to be useful in authentic settings. These two examples share some properties with the type of systems described in the next section, interactive surfaces.

2.2.3 Interactive surfaces

Interactive surfaces usually encompass applications where the spatial relationships among tangible artifacts are important. The arrangement of physical objects creates the basis model for a simulation. Interactive surfaces are often coupled with Augmented Reality (AR) techniques to project digital information directly on top of the physical model. Other types of interactive surfaces use projection from the back of the table through a semi-transparent glass. In this case the information is typically limited to the 2D surface.

BUILD-IT [Fjeld et al., 1999b, Fjeld et al., 1999a] is a brick-based application supporting engineers in the design of assembly lines and factories. It is composed of a table, augmented with a projector and a camera attached to the ceiling, and a vertical screen which gives a side view of the plant being designed. Physical bricks are used to interact with digital objects: users attach a brick to digital objects by

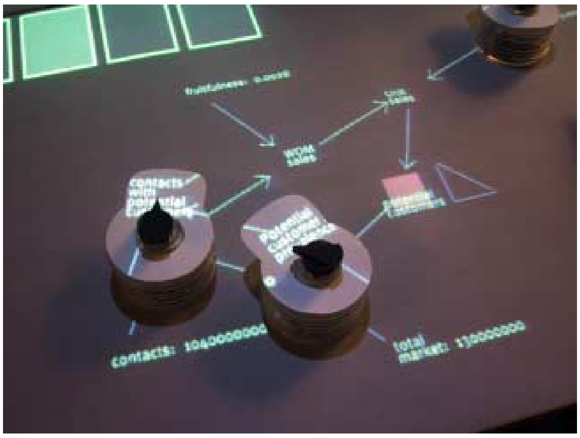


Figure 2.12: Physical pucks attached to digital data on the Sensetable [Patten et al., 2001]. Dials on top of the pucks allow users to modify digital objects' parameters.

placing it on top of them and release them by covering the brick with their hands. The association between a brick and a digital object is temporary: the meaning of the brick at any time is given by the digital representation attached to it.

Sensetable [Patten et al., 2001] is based on the same kind of interactions as BUILD-IT with physical pucks that are attached to digital objects to manipulate them (Figure 2.12). The underlying technology is however different: it uses commercially available sensing tablets, pursuing the goal of reducing latency and augmenting precision compared to vision-based systems. Unlike the bricks used in BUILT-IT, pucks have embedded functions such as dials and modifiers that are used to modify digital objects' parameters. Data can be exchanged between the interactive surface and a vertical screen, supporting applications where complex data is shown on screen, and part of it can be extracted and moved on the table for modifications. The system has been applied to chemistry and system dynamics simulations.

The ARTable [Park and Woo, 2006] is another system based on vision techniques to track physical objects, used to support story-telling activities. It has the particularity to take images from both above and below the interactive surface, where the projector is also located (Figure 2.13). Placing the projector below the interactive surface removes the problem of occlusions generated by users' bodies but has the disadvantage that it is not possible to project information on top of physical objects. Tangible artifacts are tracked thanks to fiducial markers, sort of 2D barcodes that have a pattern easily recognizable by a computer vision algorithm. Vertical displays are also available to provide additional information about objects manipulated on the table.

URP [Underkoffler and Ishii, 1999] addresses the domain of urban planning. Compared to the previous systems, it uses tangible artifacts that are associated with a unique digital object. Moreover, their physical shape corresponds to their digital counterparts. Users arrange small-scale models of buildings and road structures

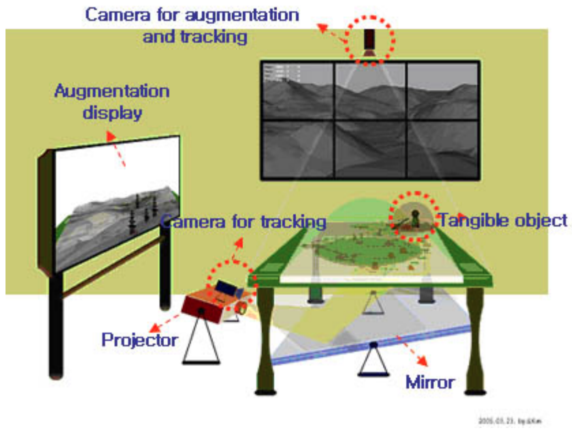


Figure 2.13: An illustration of the ARTable [Park and Woo, 2006], an interactive surface developed to support story-telling activities. It illustrates the particularity of the setting, which is to take images from both above and below the interactive surface. Two vertical displays present additional information about the objects manipulated on the interactive surface.

on an interactive surface. A projector adds digital information around the model, showing for example the shadow that would be cast by buildings at different times of the day (Figure 2.14). The system also simulates traffic, pedestrian and wind flows. Physical tools provide additional functionalities to measure distances, change a building's façade to glass such that it reflects sunlight (Figure 2.14) or modify the direction of wind. A camera object pointed towards the model displays a 3D rendering of the scene from the point of view of pedestrians, allowing designers to better visualize the resulting layout.

Illuminating clay [Piper et al., 2002, Ishii et al., 2004] introduced the concept of continuous tangible interaction, allowing users to create a landscape model using clay (Figure 2.15). A ceiling-mounted laser scanner captures in real-time the shape of the landscape and a projector displays digital information on top of it. Augmentations include colored maps showing elevation or slope at each point of the model, shortest paths (taking difficulty into account) between two points, water flow and land erosion. The system is one of the rare examples where authors explicitly described secondary interface elements: traditional GUI elements controlled with a mouse are used to set visualizations or select points on the model.

Mechanical constraints [Patten and Ishii, 2007] opened a new dimension of TUIs, providing the computer with the capacity to move physical pucks and thus the possibility to engage in a real two-way physical communication (Figure 2.16). The technology used is an array of individually actuated electromagnets situated below an horizontal surface. This system has been applied to situations where a computer tries to solve a problem moving objects on the interactive surface, like cellular telephone tower placement. Several mechanical constraints can be applied to pucks, by putting for example a rubber band around two pucks to limit the distance between

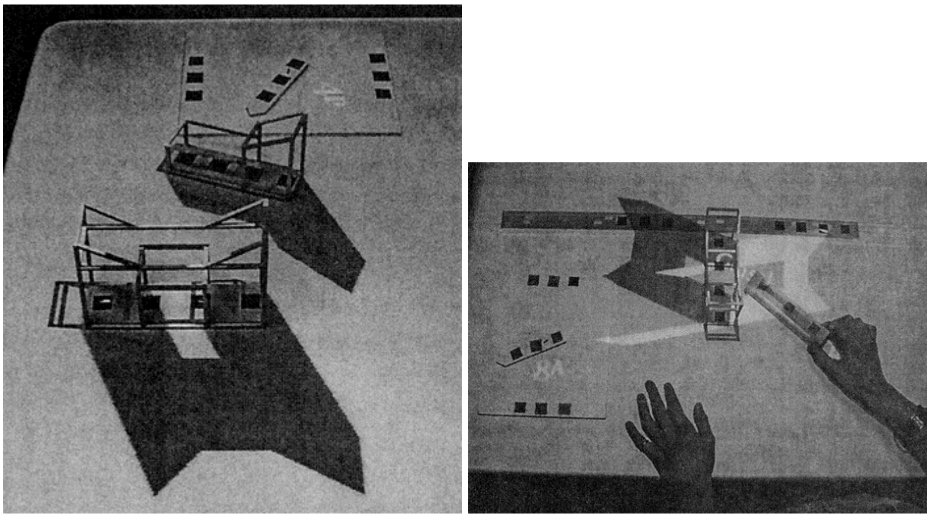


Figure 2.14: Pictures of URP [Underkoffler and Ishii, 1999], an interactive surface for urban planning. Left: shadows of two buildings represented by tangible small-scale models are shed by the system on the tabletop. Right: a user changes the material of a building to glass by touching it with the corresponding tangible tool. The building surface now reflects light and the result is displayed immediately by the system.

the two, by placing collars around pucks to ensure minimal distances with their neighbors or by placing weights on top of a puck to prevent the computer from moving it.

The Envisionment and Discovery Collaboratory (EDC) [Arias et al., 2000,Arias et al., 1997] was developed to conduct research on a large range of questions raised by the collaborative aspects of tabletop computing. These include social and cultural perspectives related with the creation of shared understanding among stakeholders, the contextualization of information to the task at hand and the creation of objects to think with in collaborative design activities [Eden et al., 2002]. The environment has been used for example to observe the placement of bus stops in a neighborhood by a heterogeneous group of people including inhabitants and urban planning experts. This early example set a milestone in terms of our understanding of social and cultural aspects of the interactions taking place around collaborative interactive surfaces.

Mapping between expected features and proposed interfaces

Most of the interfaces developed for the interactive surfaces reviewed in this section are limited to one-to-one mappings of the OoI onto tangible artifacts and DM tools. Examples of OoIs include the buildings small-scale models of URP [Underkoffler and Ishii, 1999], the clay landscape of Illuminating Clay [Piper et al., 2002] or the physical tokens of Mechanical Constraints [Patten and Ishii, 2007]. URP also offers DM tools that allow users to set the wind direction or change the surface of building

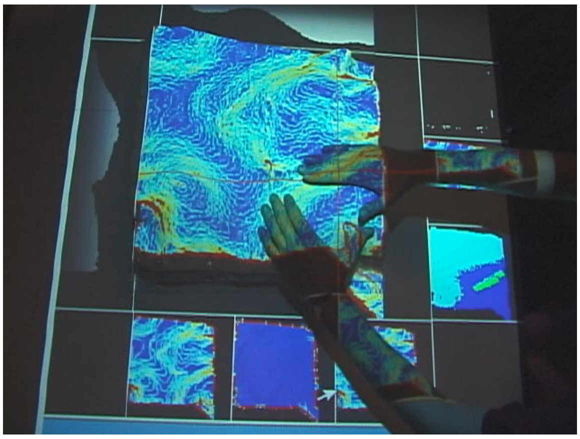


Figure 2.15: A user modeling a landscape with Illuminating clay [Piper et al., 2002, Ishii et al., 2004]. Geographic information is updated in real-time thanks to a ceiling-mounted laser. Additional information is shown on smaller side displays.

to glass. It is interesting to note the particular use of physical bricks to interact with a digital representation of the OoI in systems such as BUILD-IT or the SenseTable. They are in some sense similar to the mouse in WIMP interfaces, even though they offer richer interactions thanks to two-handed input and tactile feedback.

The main difference between interactive surfaces and the two other types of tangible systems described before is that applications developed for these systems may potentially offer a much higher level of complexity. While most of the applications encountered in constructive assembly and token+constraints systems aimed to achieve a rather specific and limited purpose, interactive surfaces are well adapted to broader, feature-rich simulations. Indeed, the applications described in this section include urban planning, landscape analysis, cellular telephone tower placement or neighborhood transportation simulations. To be useful in practice, these environments typically have to provide a large amount of parameters and options to allow users to model a large variety of situations. The TUIs developed for these environments did not aim to address this issue; the researchers focused on other aspects such as the exploration of novel interaction techniques or the potential of interactive surfaces to support collaborative problem-solving activities. There is nonetheless a large gap between the number of actions that can be performed by users with these interfaces compared to their expectations in an authentic setting. We further discuss this issue in Section 2.5.

2.3 Taxonomies and analysis frameworks

A number of frameworks and taxonomies have been proposed to facilitate the description and comparison of systems based on tangible interaction. They can be classified in three groups. A first type of frameworks focuses on the different types of interface elements used in TUIs; the second offers taxonomies based on the level of coupling between physical and digital interfaces; the third and last type

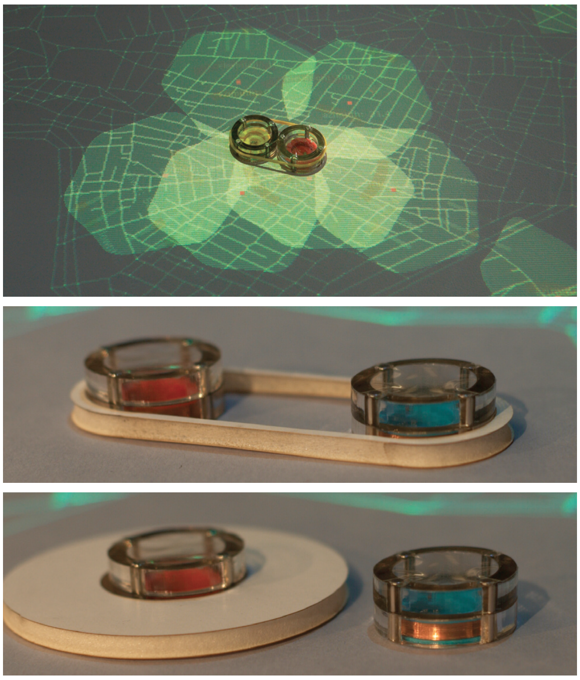


Figure 2.16: Mechanical constraints: an interactive surface that is able to move physical pucks [Patten and Ishii, 2007]. Top: example of a cellular telephone tower placement: digital information displays the area covered by each tower. Middle: a mechanical constraint applied to two pucks that limits the maximal distance between them. Bottom: another mechanical constraint, used to ensure a minimal distance around a puck.

describes TUIs based on their impact on social interactions. The most influential works of each type are reviewed below.

2.3.1 Relationships among tangible artifacts

Holmquist et al. proposed a classification of physical artifacts used in TUIs in three groups: *containers*, *tokens* and *tools*. Containers are generic objects that can be attached to any kind of digital information but do not necessarily share any similarity with it. They are usually associated with data on a temporary basis. This is the case of the marbles used by the *Marble Answering Machine* [Moggridge, 2006], MediaBlocks [Ullmer et al., 1998] or the bricks of the BUILT-IT system [Fjeld et al., 1999b]. Tokens correspond to physical objects which share some physical properties with the digital object they represent. They are usually associated to a fixed tangible artifact. Examples of tokens include the creatures built with Topobo [Raffle et al., 2004] or the buildings small-scale models used in URP [Underkoffler and Ishii, 1999]. Tools, finally, represent computational functions and are used to manipulate digital information, such as Senseboard's command pucks [Jacob et al., 2002] or URP's tangible artefacts used to measure distances or change buildings' material.

Figure 2.17: Users working on transport planning task with the Envisionment and Discovery Collaboratory (EDC) [Arias et al., 2000, Arias et al., 1997]. It has been developed with the aim to deepen our understanding of social and cultural aspects of collaborative tabletop environments.

Shaer et al. proposed a paradigm called *Tangible and Constraints* (TAC), which is based on a set of core constructs that aim to facilitate the development of TUIs [Shaer et al., 2004]. According to the authors, these constructs are the equivalent of what widgets and events are for GUIs. The TAC paradigm is motivated by the technical challenges offered by the specific properties of TUIs, which stem for example from the mix of virtual and physical objects, the potential interactions among tangible artifacts or the lack of standard input and output devices. The paradigm defines three components: a *pyfo* is a physical object that is part of a TUI; a *token* is a graspable pyfo that represents either digital information or a computational function; a *constraint*, finally, limits the behavior of the token with which it is associated. The goal of constraints is to facilitate the use of tokens by providing some guidance to users. A TAC is defined as a relationship between a token, the digital information to which it is associated and a constraint. A TUI can then be described as a set of TAC relationships. In the case of URP [Underkoffler and Ishii, 1999] for instance, the material tool is a token and buildings are constraints. The relationship exists only when the tool touches the building, at which time the corresponding action has to be triggered by the system: the building material changes. The TAC paradigm has been used to describe very different tangible environments. Authors argue that it provides a more abstract view of TUIs that can facilitate their development [Shaer et al., 2004].

2.3.2 Coupling between physical and digital objects

Koleva proposed a classification of interface elements based on the *degree of coherence* between physical and digital objects [Koleva et al., 2003]. Six levels are proposed, from the weakest degree offered by *general purpose tools* (e.g. mouse) through *proxy* interface objects such as Senseboard's pucks [Jacob et al., 2002] to artifacts which give the illusion of being the same as the objects they represent. This is the case if *they are visible only one at a time, making smooth transitions between the physical and the digital space* [Koleva et al., 2003]. The framework proposes that the degree of coherence comes from the strength of the link between the interface object and its digital counterparts, which depends on a set of six properties. For instance, the transformation property describes whether the movements of the user are mediated in a literal way, which offer a stronger degree of coherence (e.g. moving a building in URP [Underkoffler and Ishii, 1999]) or not. Another property is the lifetime of a link: a marble is only temporarily associated with a message in the *Marble Answering Machine* [Moggridge, 2006] and provides a lower degree of coherence than Senseboard's tokens [Jacob et al., 2002] which are continuously attached to the same paper. The authors used the framework for example to identify the fact that only a few TUIs can physically react to users' actions, such as Mechanical Constraints [Patten and Ishii, 2007].

Fishkin takes another approach which describes relationships between physical and digital objects along two axes, metaphor and embodiment. The *degree of embodiment* describes how closely the input focus and the output focus are tied. Fishkin argues that increasing the embodiment is a way to decrease the *cognitive distance* between the input and the output. Four levels are proposed:

- *Full* - the input and the output are merged into a unique device, like for example the pucks in the mechanical constraints system proposed by [Patten and Ishii, 2007];
- *Nearby* -in this case the input and output are not merged but happen nearby, as is for example the case in URP [Underkoffler and Ishii, 1999] with the shadow projected around the buildings;
- *Environmental* - the output takes place around the user, as would be the case with an audio feedback or ambient light adjustments;
- *Distant* - in these situations, the output is disconnected from the input and takes place for example on a screen (e.g. ActiveCube [Watanabe et al., 2004]) or even in another room.

The *degree of metaphor* represents the similarity of the effect of a user action in the real and the digital worlds. Five levels are proposed:

- *None* - the interface is not connected to any real-world analogy (e.g. command-line interfaces);
- *Noun* - the elements of the interface share a similar shape, look or sound with real-world objects, but the actions that can be performed on them are not the same. This is the level of metaphor of GUIs, where application windows are analogous to real sheets of paper on desktop, but most of the physical actions possible with real paper are not possible on the screen;
- *Verb* - in this case, the shape of the tangible component is irrelevant but the actions that are performed are based on similar gestures (e.g. bricks in BUILD-IT [Fjeld et al., 1999a]);

- *Noun&verb* - at this level both the noun and the verb are now related (e.g. building small-scale models in URP [Underkoffler and Ishii, 1999]);
- *Full* - no analogy at all has to be made by the users, they have the impression to manipulate the digital objects directly (e.g. landscape model in Illuminating Clay [Piper et al., 2002]).

2.3.3 Impact on social interaction

Hornecker et al. proposed a framework which focuses on the social aspects of tangible interactions [Hornecker and Buur, 2006]. The authors argue that it fills a gap in the literature on tangible computing regarding our understanding of the reasons why this interaction modality works well for users, in particular in collaborative settings. The framework builds on four core themes of TUIs and aims at supporting the analysis and design of tangible environments. The themes are *tangible manipulation* (interaction with physical objects), *spatial interaction* (inherent property of TUIs, body interactions), *embodied facilitation* (interface creates a structure that shapes social interactions) and *expressive representation* (interrelation of physical and digital elements).

2.4 Learning with tangibles

2.4.1 Theoretical background

One of the largest domains of application of Tangible User Interfaces is education, in particular for young children. The idea of using physical objects in learning activities, called manipulatives, is not new. Montessori [Montessori, 1912] developed a century ago a learning approach based on manipulatives described as *materials for development*. Montessori put a strong emphasis on children's natural learning tendency and believed that physical tools would engage children in self-directed, meaningful activities. Friedrich Froebel, who developed the concept of the *kindergarten* in the middle of the 19th century, pointed out the importance of play and self-discovery in the development of children. He developed a set of manipulatives, including balls, blocks, sticks, tiles and rings, known as *Froebel Gifts* which were carefully designed to help children discover patterns and forms found in nature.

Research in developmental psychology also brings evidence supporting the use of manipulatives in education. Piaget and Bruner have shown that children are able to solve problems using concrete manipulatives even if they are not yet able to formulate them at a symbolic level [Piaget, 1964]. An example is the discovery of mathematical concepts like prime numbers, as observed by Bruner in an experiment where children uncover it using arrangements of beans and observing that some quantities can not be laid out in complete row and column layouts [Bruner and Kenney, 1965].

Bruner defines three main levels of representations [Bruner, 1966]. The *enactive* level corresponds to representations that are experienced in a physical way. The *figurative* level encompasses representations which have some resemblance with the represented information (e.g. a map of a room shares a spatial relationship with the room it represents). At the *iconic* level, there is no more relationship between the representation and the concept it represents. Bruner argues that children learning concepts in a domain have to pass sequentially by these three forms of representation which continue to co-exist.

Piaget's development theory also involves a progression through different forms of representation at four stages [Piaget, 1974], but it takes place at a global development level compared to the domain-specific level proposed by Bruner. At the *sensorimotor stage*, children build initial concepts about reality through physical interaction. At the *pre-operational stage*, concrete physical situations are needed for the child who is not yet able to reason at an abstract level. Abstraction skills develop during the stage of *concrete operations*, where children start conceptualizing from their experiences and where abstract problem solving becomes possible. When they reach the stage of *formal operation*, children are able to recognize relationships between abstract properties.

Research on the use of gestures shows that children understand certain concepts before being able to express them using an appropriate discourse. Roth [Roth, 2000] drew three main claims about the relationship between gestures and discourse from observations of children during inquiry science lessons. First, when the appropriate discourse is not yet available to them, children's gestures already correspond well to the concepts they explain. Second, during the initial development of the scientific discourse, gestures tend to take place slightly before the associated utterances. Finally, when children become progressively familiar with a topic, language and gestures begin to coincide.

Papert observed that children's personal sensorimotor experience developed by moving in their three-dimensional environment is the source of a deep and implicit spatial knowledge. He developed the Logo programming environment [Papert, 1980], which let children program the movements of a turtle. Children are first asked to produce the desired movement themselves, actually moving through the room. The goal is to let them progressively discover the correct algorithm that gets the turtle to produce the same movement.

2.4.2 Conceptual frameworks

Adding digital capabilities to manipulatives created a need for novel conceptual models used to categorize and explain their benefits.

Marshal et al. [Marshall et al., 2003] proposed a conceptual framework for TUIs based on Heidegger's notions of *readiness-to-hand* and *presence-at-hand*, describing the way users treat a tool. Readiness-to-hand refers to situations where we use tools or representations without explicitly being aware of their properties but rather focus our attention on the task we are performing. Presence-at-hand refers to the opposite situation where the tool or representation we use is at the center of our attention. Building on Ackerman's work [Ackermann, 1999] stating that *effective learning often involves temporarily standing back from the learning experience to reflect upon it in more objective terms*, they argue that an effective use of digital manipulatives comes from cycling between the two modes of readiness-to-hand

and presence-at-hand.

Zuckerman et al. [Zuckerman et al., 2005] focused on the use of physical manipulatives for teaching abstract concepts. They proposed a new classification, divided in two classes: *Froebel-inspired Manipulatives* (FiMs) and *Montessori-inspired Manipulatives* (MiMs). FiMs are building toys, allowing children to design real-world things such as ActiveCube [Watanabe et al., 2004] or Topobo [Raffle et al., 2004]. MiMs are building blocks as well but focused on modeling conceptual and abstract structures like for example SystemBlocks [Zuckerman and Resnick, 2003]. They argue that there are three advantages of using TUIs to teach abstract concepts:

Sensory engagement: TUIs correspond to the natural way children learn, engaging multiple senses in a constructive process;

Accessibility: dramatically improve accessibility to younger children, to people with learning disabilities, and to novices;

Group learning: TUIs provide a multi-hand interface, do not give the control to one person, facilitate natural group interaction, and promote group discussion.

In their opinion, the main difference between digital and traditional manipulatives lies in their ability to model temporal and computational processes. They are for example able to record and plot data such as the position and the speed of an object over time.

Price [Price, 2008] argues for the central role played by representations in tangible environments, describing the facility to combine representation with artifacts and the environment as a unique feature or such systems. Her argument draws on research in psychology and cognitive sciences which demonstrates the importance of external representations in supporting cognition [Scaife and Rogers, 2003]. A framework is proposed, borrowing from other frameworks presented in section2.3 but focusing on key characteristics of representation-artefact relationships through four dimensions of association:

Location: different location couplings, which can be discrete (input and output separated), co-located (input and output are contiguous, e.g. projections on top of physical objects) or embedded (a digital effect occurs within an object). This characteristic is similar to the degree of embodiment as defined by [Fishkin, 2004];

Dynamics: refers to the different information associations that can be created between artifact and representation. Two aspects are considered. The first is *intentionality*, since digital effects can be expected, after a user action for example, or unexpected and thus potentially trigger discovery or discussion. The second aspect is *cumulation*, representations evolving over time through continuous interaction or information recorded by the system, which can trigger different types of inferences from the learners.

Correspondence: divided among *physical correspondence*, the degree to which the physical properties of artifacts are related to digital objects, and *representational correspondence*, related to the meaning mapping between physical and digital objects, which can trigger different levels of reflection in the learners.

Modality: often limited to visual representations, but it is important to understand the role of different modalities for learning.

As stated by the author, the goal of this framework is not provide a prescriptive comparison system for research but rather a structure in which research can be positioned.

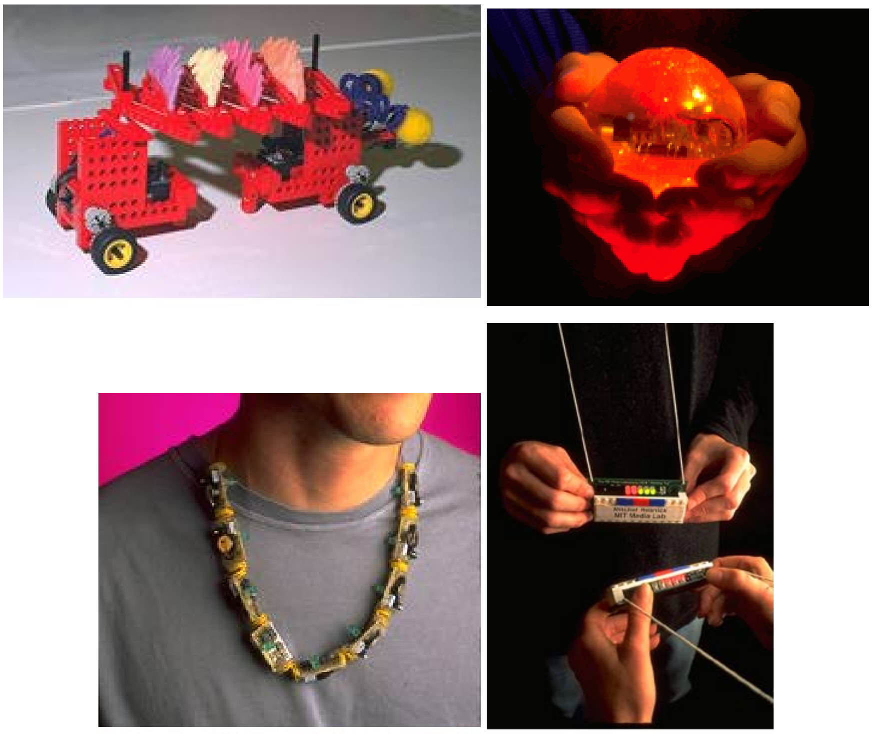


Figure 2.18: Picture of digital manipulatives [Resnick et al., 1998], tangible learning toys which aim to facilitate the understanding of dynamic systems by young children. Top left: a vehicle built with both LEGO and *programmable bricks* used to teach basic principles of feedback and control. Top right: the bitball, a ball that senses its movements and displays acceleration data. Bottom left: a necklace made of *programmable beads* that let children experiment with cellular automata concepts. Bottom right: *thinking tags* worn by two children exchanging data.

2.4.3 Tangibles in education

Resnick et al. introduced the term *digital manipulatives* to refer to their application of TUIs concepts to education [Resnick et al., 1998]. They developed a set of computationally augmented toys, with the aim to facilitate the understanding of dynamic systems for young children, taking advantage of their familiarity with these objects. They implemented these concepts through four typical children's toys: blocks, beads, balls and badges (see Figure 2.18). *Programmable bricks*, standard LEGO bricks with embedded digital capabilities allowing them to receive

Figure 2.19: Children during a problem-solving task with *AlgoBlock* [Suzuki and Kato, 1993]. Physical blocks are arranged to control a submarine blocked in a maze.

information from sensors and control motors and light, allow children to discover basic principles of feedback and control by programming autonomous creatures. *Programmable beads* were designed to let young children experiment with cellular automata concepts, using either pre-programmed or customized beads. The *BitBall* is a programmable ball which can sense its movements and react accordingly, allowing children to run experiments based on acceleration data displayed through real-time visual feedbacks (LED embedded on the ball) or wirelessly transmitted to a computer for later analysis. *Thinking Tags* are wearable objects that display information but also communicate with tags worn by other persons. They can be used for instance in experiments about the spread of epidemics, showing how an electronic virus jumps from one child to the others as they move in the classroom.

Approaches based on tangible programming techniques have received a strong interest and were thus not limited to Resnick et al.'s work. *AlgoBlock*, developed to study collaborative problem-solving [Suzuki and Kato, 1993], allows children to control a submarine through a maze using relatively large computationally augmented cubes (Figure 2.19). Wyeth and Purchase proposed a system targeted to younger children called *Electronic Blocks* [Wyeth and Purchase, 2002]. Blocks can be easily attached together to create programs. Each block has a predefined functionality, divided in three classes: *sensor blocks* can detect light, sound and touch, *action blocks* can create light, sound and movement, and *logic blocks* add logic functions to programs, like delays, repeat or negate signals. Topobo [Raffle et al., 2004], already described in Section 2.2.1, allows children to build creatures using a combination of passive and motorized components, animate them by physically moving the parts and finally observe the movement repeated by the system.

Fernaeus and Tholander proposed a tangible environment supporting children's

Figure 2.20: Children creating a screen-based play by placing characters on a carpet [Fernaeus and Tholander, 2006] and mapped to the screen.

Figure 2.21: A child capturing a texture with the I/O Brush [Ryokai et al., 2004] while drawing on a screen.

collaborative construction of screen-based plays [Fernaeus and Tholander, 2006]. Children program their play on a large carpet placed on the floor of the classroom in front of a large screen (Figure 2.20). They add characters to the screen by placing corresponding cards on the carpet: their position is mapped onto the screen.

Among the advantages of TUIs in education, the possibility to engage children in playful, interactive and creative activities is often cited. *The Hunting of the Snark* is a good example of these potential applications [Price et al., 2003]. In this game, pairs of children have to find a mysterious creature, the Snark, using a range of sensing tools allowing them to gather some clues about the Snark. Experiments conducted with children pointed out important aspects of this playful approach, including excitement and engagement of children, exploration through interaction, reflection of their experience, creativity, imagination and collaboration. The Hunting of the Snark, unlike most of the systems reviewed until now, does not take place at a fixed

Figure 2.22: Many applications of TUIs in education were developed to support storytelling activities in the classroom. A child telling a story on StoryMat [Ryokai and Cassell, 1999], which records her voice and movements that can be reused for future stories.

location but is distributed among a large physical space. This approach has been conceptualized in a framework proposed by Price and Rogers [Price and Rogers, 2004] for the development of digitally augmented physical spaces: interaction with physical tools, physical movements and combining artifacts with each other. Another example of applications supporting playful learning and creativity is the I/O Brush [Ryokai et al., 2004], which objective is to let children think about colors and textures. It takes the shape of a physical paintbrush with an embedded camera. Children pick colors and textures by pointing it at any object and draw with them on an interactive surface (Figure 2.21).

Many applications of TUIs in education were developed to support storytelling activities in the classroom. StoryMat [Ryokai and Cassell, 1999] supports collaborative fantasy play and storytelling (Figure 2.22). It records children's voice and movements and allows collaboration to take place among co-present peers but also with previous recorded stories. Stanton et al. developed the *magic carpet* [Stanton et al., 2001], a tangible interface to the KidPad, a collaborative drawing tool used in classrooms to create stories. Pressure-sensitive mats and physical artifacts are used by children to navigate through their stories and support their reenactment to audiences (Figure 2.23). With *tangible viewpoints* [Mazalek et al., 2002], children navigate through multiple viewpoint stories by placing physical characters in the form of pawns on an interactive surface (Figure 2.24). Narratives corresponding to this character and position are displayed on a nearby screen.

Interactive surfaces have also been used in education, supporting exploration and discovery of concepts through the collaborative configuration of physical simulations. *Illuminating Light* [Underkoffler and Ishii, 1998] proposes a set of physical artifacts representing various optical elements like laser beams, mirrors and reflectors. These elements can be freely arranged by children on an interactive surface which simulates in real-time the path of laser beams and their interactions with other elements (Figure 2.25). Caretta [Sugimoto et al., 2004] is an urban planning

Figure 2.23: Children reenacting a story on the pressure-sensitive Magic Carpet, previously created with KidPad [Stanton et al., 2001].

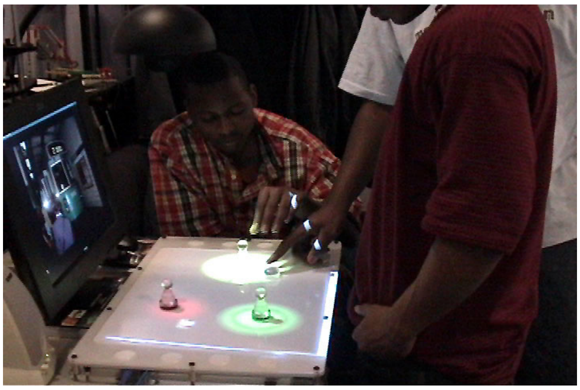


Figure 2.24: Children navigating through a multiple viewpoint story with tangible pawns [Mazalek et al., 2002], with corresponding narratives displayed on a screen.

application running on a sensing board using RFID technology to detect objects. Children redesign a town with small-scale models of houses, stores and office buildings, and a simulation allows them to evaluate its impact on the ecosystem (Figure 2.26). Handheld devices allow children to test alternatives for a limited area of the town in a private space before sharing them with the rest of the group by placing the handheld close to the interactive surface. Several boards can be interconnected and illustrate the effects of one town on the others.

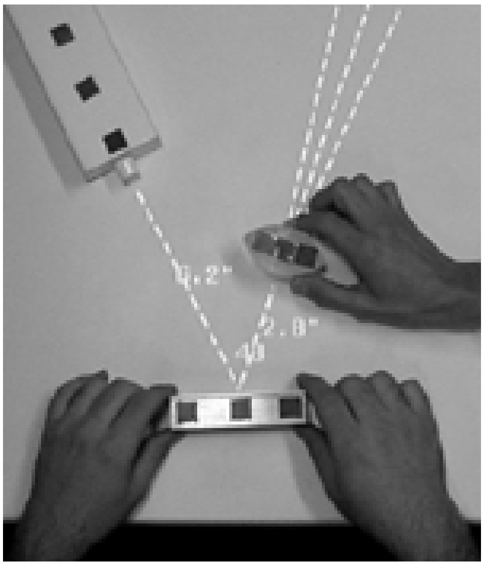


Figure 2.25: A picture of *Illuminating Light* [Underkoffler and Ishii, 1998] in use: a laser beam is reflected by a mirror before passing through a lens that separates different light components.

2.5 Open Issues

2.5.1 Scalability of Tangible User Interfaces

Most of the systems we reviewed in the previous sections aimed at exploring the new opportunities offered by the use of tangible artifacts as interfaces to computer systems. The frameworks and taxonomies developed for TUIs have been mainly interested in the individual mappings between physical objects and their digital counterparts. With the underlying technologies reaching a level of maturity high enough to ensure a certain stability and robustness of tangible environments, it is time to address questions related to the application of TUIs to real-world situations. This implies considering the mapping of digital and physical objects not only at the individual level but at the application level. Compared to systems developed for research purposes, focusing on the exploration of interaction techniques, real-world applications tend to be more complex and propose a larger set of functionalities to users. These functionalities have to be mapped onto elements of the interface to be available to users, which is challenging in tangible environments where interaction is based on the physical manipulation of tangible artifacts usually offering a one-to-one mapping with digital objects.

Sharlin et al. [Sharlin et al., 2004] propose to consider physical/digital mappings as a success criteria for TUIs. They introduce three heuristics to evaluate them: successful spatial mappings, unified input and output and support for trial-and-error activities. They argue that *highly specialized TUIs will prove to be more valuable than generalized TUIs in the long run*, but also recognize the shortcoming of the approach, which results in practical difficulties and higher development costs due to the

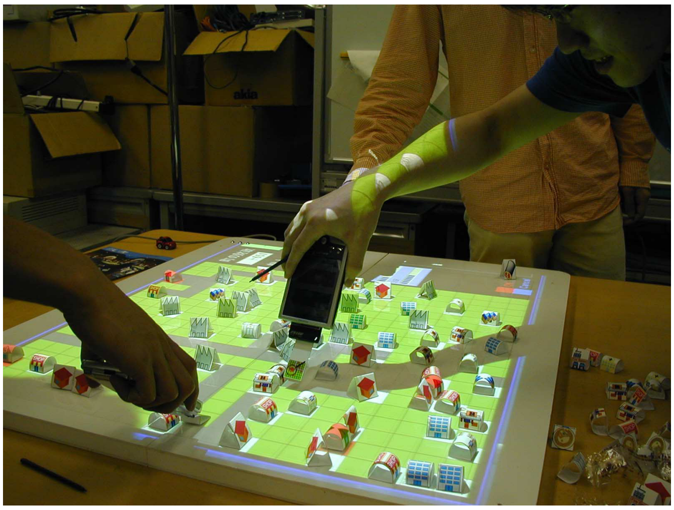


Figure 2.26: Children redesigning a town with Caretta [Sugimoto et al., 2004]. Handheld devices are used to test solutions in an individual way before transferring them to the shared environment.

high specialization of the interfaces. This is practically not feasible in a complex application since each parameter would then be represented by a specific tangible artifact. The solution to the mapping between TUIs and complex applications will then probably have to be a trade-off between specificity and generality.

Among the three main types of TUIs reviewed in Section 2.2, we have seen that the trade-off between specificity and generality is particularly relevant for interactive surfaces. Constructive assembly and token+constraint systems are mostly used for applications where the input and output language is fairly limited and can thus be fully embedded in the physical artifacts of a TUI (Figure 2.27). This is the case for instance of the Marble Answering Machine [Moggridge, 2006]. The only objects directly manipulated by users are messages recorded during missed calls, represented as colored marbles. The possible actions are limited to listening to a recorded message, call back the person who left the message and delete it. Each action is achieved by placing the marble on a specific part of the machine, which shape clearly identifies its function. The same is true for Topobo [Raffle et al., 2004] which offers a rich discovery environment to children through a limited set of construction blocks. In the two examples given above the purpose of the system is well-defined and limited to a clear set of actions and manipulable entities.

The problem is different for interactive surfaces, often combined with simulations and targeted to collaborative problem-solving and learning situations where groups of users explore solutions in potentially complex domains. In these cases, large numbers of parameters and options can be proposed to give users the flexibility they need to model a large set of situations. Environments like URP [Underkoffler and Ishii, 1999], which allow users to arrange building on an interactive surface and augment them with digital information, offer only a limited set of possible

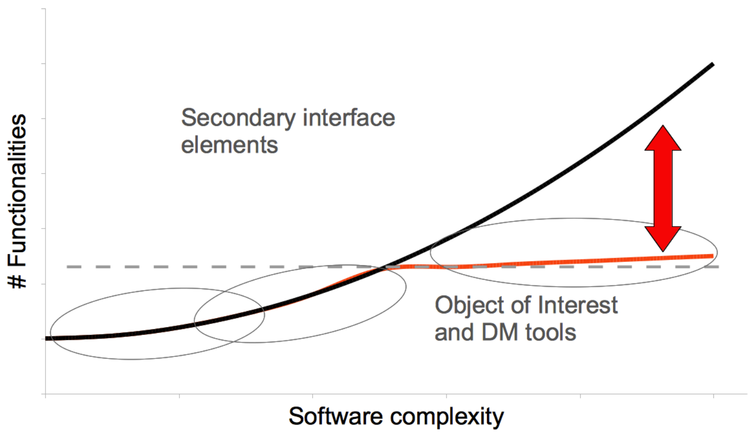


Figure 2.27: The scalability issue of TUIs. The red curve shows the typical amount of features implemented by the tangible environments developed for research purposes compared to the amount needed for real-world applications. The three ellipses show the location of the three main types of TUIs. Constructive assembly (left) and token+constraints (center) systems often correspond to special purpose, focused applications with a low complexity. They usually offer a good mapping between the features needed and the actions available through the TUI. The situation is different for interactive surfaces (right) which are typically used for complex simulations that need to provide users with a large amount of customizable parameters.

actions beyond moving buildings. While the environments developed so far were sufficient to illustrate tangible interaction techniques and explore the potential of such approaches, users working with them in real-world situations will expect a much broader set of parameters than those currently offered (Figure 2.27).

TUIs are thus facing a trade-off between scalability, which encourages the use of generic interface elements, and richness of interaction, a core strength that comes from the rich physical affordances offered by specific tangible artifacts. This dissertation addresses this issue by exploring the use of hybrid interfaces. We propose paper as a complementary interface to TUIs and implement a trade-off between specificity and scalability by assigning different responsibilities to each interaction modality. Tangible artifacts specifically designed for each application offer rich physical affordances while paper brings a standard, generic set of interface elements that can be used to control and visualize an arbitrary number of parameters. This hybrid approach is described in more details in Chapter 4.

2.5.2 Learning effectiveness of physical manipulatives

Despite a strong interest and theoretical background supporting the learning effectiveness of physical manipulatives, formal experiments failed to show repeated positive results. A meta-analysis reports rather inconsistent and limited effects of manipulatives on learning outcomes [Sowell, 1989]. Strong critics have thus been formulated about the use of manipulatives in learning contexts, in particular in the field of mathematics where they have been mainly developed.

This issue is pointed out by [Uttal et al., 1997] who argues that a reason why children face difficulties when learning with manipulatives comes from the need to interpret the physical artifact as a representation of an abstract concept. Challenging the traditional view that manipulatives are useful because they are concrete and thus save children from having to reason at an abstract level, they propose to consider manipulatives not as concrete representations but as symbols themselves. It is then fundamental to understand how children perceive and understand symbolic relationships and the link between manipulatives and the concepts they represent. Good manipulatives should not be interesting by themselves since children may focus on them instead of considering the concept they represent. Another advice given by the authors is to avoid the use of objects that are already known (e.g. food or toys) since they may also disturb their understanding as symbols.

Clements also criticizes the argument stating that manipulatives are effective because they are concrete [Clements, 1999], for two main reasons. The first is that *it can not be assumed that concepts can be read off manipulatives*: physical manipulation of tangible artifacts does not necessarily mean that the underlying concepts will be made available to the learners. The second reason is that *physical actions with certain manipulatives may suggest different mental actions than those we wish students to learn*, such as children performing additions with the help of external tools like a numbered line and getting the right answer without actually mentally adding the numbers.

The relationship between physical manipulations and understanding of underlying concepts has been addressed by Marshall et al. [Marshall et al., 2003] in their discussion about the use of TUIs in learning contexts. Their proposition that effective learning comes from a cycle between the two modes of *ready-to-hand* and *present-to-hand*, already pointed out above, outlines the need for phases where students reflect about their activity with tangible artifacts.

As pointed out by [Marshall, 2007], there is a lack of comparative work evaluating the effectiveness of TUIs, despite the large number of systems developed in this field. This dissertation contributes to this necessary effort by the development and evaluation of a tangible learning environment used in an authentic context. In particular, it proposes a generalizable solution for supporting the mode of present-to-hand or reflection phases in the use of tangible environments, thanks to a Paper User Interface (PUI). Chapter 5 introduces the context where this work took place and describes in more details the approach we propose.

Chapter 3

Paper-based User Interfaces

DESPITE the advent of computers and the increasing place taken by technology in our daily life, we still rely on traditional paper in many situations. We use it at the workplace to take notes or sketch ideas, we stick reminders on our computer screens and often print out documents we have to read. At home, we use it to write down our shopping list, to leave notes to our flat mates or family. Reading is mostly done on paper since it offers many advantages over computer screens. A laboratory study reported by [O'Hara and Sellen, 1997] comparing reading from paper or online has shown that paper is superior thanks to its support for annotations while reading, quick navigation and flexibility of spatial layout, and also had a positive effect on participants' understanding of the text. Shah and Brown [Shah and Brown, 2005] argue that paper offers high reflectivity and contrast, flexibility, light weight and ease of portability, low cost and wide viewing angles, while computer screens suffer from low reflectivity, high emissivity, high cost, high power consumption and bulkiness. Schilit et al. summarize the affordances of paper compared to on-line reading through five main categories:

Tangibility: physical properties of sheets or stacks of paper allow them to be held, moved, folded, rotated, . . . but also support effortless navigation [O'Hara and Sellen, 1997].

Free-form ink annotation: taking notes on real paper requires little cognitive overhead and the visual separation of annotations from the printed text highlights their conceptual difference.

Page orientation: the fixed layout of paper documents facilitates navigation, skimming and spatial memory, which is often lost on computer systems.

Multiple displays: paper documents can be spatially arranged on a desk and thus offer an *unlimited* number of displays, which is less cumbersome than switching between windows on a desktop computer.

Sharing: paper documents can be easily shared by handing them to other people, and more than one person can work with a document at the same time.

A range of technologies have been developed in recent years with the aim to create *electronic paper*, digital devices with paper-like properties (e.g. [Comiskey et al., 1998,Hayes and Feenstra, 2003,Shah and Brown, 2005]). Commercial products have

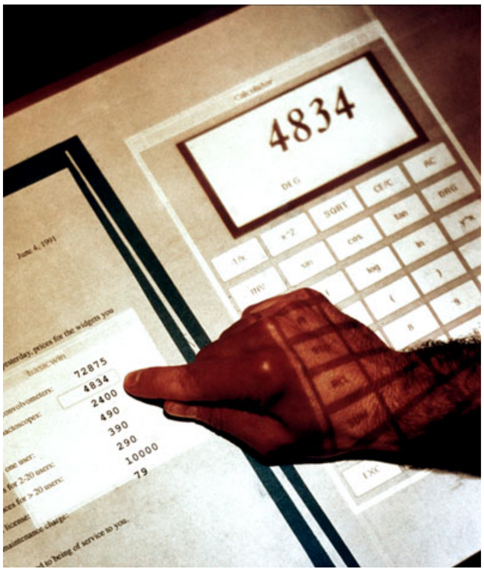


Figure 3.1: The DigitalDesk calculator [Wellner, 1991]: a user copies a number from a printed document to the calculator by pointing at it.

been available for a couple of years, like for example IREX's [1] Iliad or Sony's Reader [2]. Initially limited to niche markets, electronic books recently became mass-market products with the arrival of Amazon's Kindle, which counts on a large content base and allows people to download books from anywhere thanks to its wireless connectivity. Despite these efforts and commercial successes, electronic paper is still far away from the unique flexibility of paper. The digital reading experience became better but many other properties of paper like price, availability, touch and feel are missing. One would not treat an electronic paper device in the same way as a traditional paper document since it would break: flexible displays have long been announced but are not yet an everyday reality. Where paper offers freedom and immediacy, digital devices add menus and formalisms that, even if limited, are enough to disturb and slow down simple actions like annotating a document or sketch an idea.

Researchers in Human-Computer Interaction (HCI) have since long recognized the qualities of paper, but also its limitations compared to digital techniques: paper is a static medium and can thus not be easily modified, searched or indexed; it is also expensive to duplicate, distribute and archive [Guimbretiere, 2003]. Research efforts have thus be directed towards mixed solutions which take advantage of the opportunities offered by digital devices while keeping the specific properties of paper. According to Wellner, typical office workers divide their time between two related but isolated activities: manipulation of physical paper documents (*paper pushing*) and electronic work on a desktop computer (*pixels pushing*) [Wellner,

[1] http://www.irextechnologies.com
[2] http://www.sony.com

1991]. His DigitalDesk merged these two interaction spaces into one, by placing a camera and a projector above a standard office desk, with the following three main characteristics:

- it projects electronic images down onto the desk and onto paper documents,
- it responds to interaction with pens or bare fingers,
- it can read paper documents placed on the desk

Wellner described several potential applications, often not actually implemented but presented as fake demonstrations used to illustrate the possibilities offered by Paper User Interfaces (PUIs). The DigitalDesk Calculator, for instance, projects a virtual calculator onto the desktop. Users interact with it by taping on projected buttons, but can also enter numbers by pointing at them in paper documents (Figure 3.1). Another example is the DoubleDigitalDesk, which allows two remote users to collaborate: documents and hands of each user are projected onto the desk of the other user, allowing them to interact with remote documents and stay aware of the actions of their peer.

Johnson et al. [Johnson et al., 1993] point out the primary role played by paper as a communication media, thanks to its physical properties that make it easy to use, transport, store, and cheap to manufacture. However, it has the disadvantage to be a passive medium, which contents are not easily manipulated compared to computers which offer more possibilities for handling, communicating, filing, and processing information. They introduced the concept of the *paper user interface*, referring to systems where ordinary paper controls computer systems. They argue that this approach has two main advantages over traditional computer interfaces: people are accustomed to use paper, which means that the necessary infrastructure is available (pencils, erasers, fax machines, typewriters, ...), and people know how to use it such that learning how to use paper interfaces is minimal. They introduced the notion of a *form* as a paper interface to computer applications, standard pieces of paper with both machine- and human-readable content. *Cover sheets*, similar to traditional paper forms, act as interfaces to a document services system, the XAX paper server. Each cover sheet contains a set of elements that can be set by users through annotations (e.g. check boxes) and transmitted to the server by scanning or faxing the page. Placed in front of a document, cover sheets can be used to give instructions to the server telling it which actions have to be performed on the document (e.g. copy n times, archive in a specific location, ...), as demonstrated by the Protofoil system [Rao et al., 1994].

Two main approaches have been followed by researchers working in the field of PUIs: paper is either used as a document, with digital capabilities aiming at enhancing its possibilities, or as an interface to computer applications, where affordances of paper are used to create intuitive and rich interactions. The early works presented above illustrate these two approaches: Wellner used paper as documents augmented with digital content and tools, while Johnson et al. proposed an interface to a computer system aimed at managing documents.

We now review relevant work in the field of PUIs. The two first sections address systems following the two approaches highlighted above. Two other sections focus on specific areas relevant for this dissertation: hybrid systems mixing tangible and paper-based user interfaces and applications developed in learning environments.

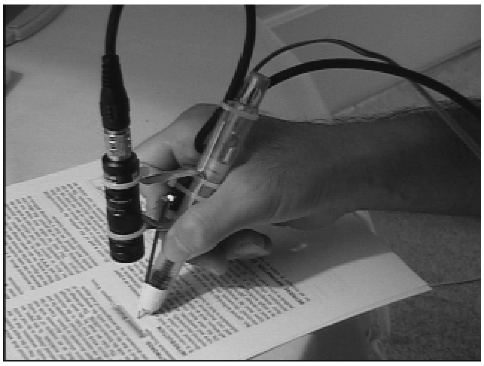


Figure 3.2: The augmented pen developed for the PaperLink system [Arai et al., 1997]. The camera attached to it allows for instance the transmission of words to the computer but is also able to read hand-written commands.

3.1 Augmented paper documents

3.1.1 Synchronizing paper and digital documents

The *InteractiveDesk* [Arai et al., 1995] aims at facilitating the retrieval of electronic documents by allowing users to attach them to real objects such as scrapbooks or folders. Objects are detected by a camera pointing towards the desk surface. When an object is recognized, a list of documents attached to it are displayed on the computer screen and can be directly opened. Adding a link between a document and an object is also done on the computer screen, through extensions of existing applications.

Paperlink uses a pen augmented with a camera to interact directly with paper documents [Arai et al., 1997] (Figure 3.2). The pen can be used to either transmit a word to a desktop application (e.g. translator) or to read commands in the form specific patterns that trigger an action. This allows for example the creation of a hyperlink between printed content and digital information stored on the computer, displayed when the link is read again. An interesting feature of the system is that it can work with any document, but additional features are available if content is known (e.g. cross-references within the document) or controlled (e.g. pre-printed commands and hyperlinks).

Schilit et al. proposed to use tablet computers as hybrid devices to support active reading activities [Schilit et al., 1998]. They argue that the form factor of tablets coupled with an interface based on the paper document metaphor keeps some important properties of real documents like physicality, ease of navigation and free-form annotations, while adding digital capabilities to them. Despite the efforts put in the development of tablet computers and the great expectations they generated, these devices have not encountered a big success yet. We currently observe a second wave of interest for tablet computers, led by Apple's iPad and surfing on the success of multi-touch mobile phones. It will be interesting to see if this new generation, which benefits from development efforts already invested in applications for mobile devices will manage to enter our everyday life and stay there for the longer-term.

Several researchers tried not to give away any advantage of either digital or paper documents by supporting seamless transitions between them. Depending on the situations, users may decide to handle a document online or find more convenient to print it. The *Transworld model* [Ito et al., 1999], proposed by Ito et al., synchronizes printed documents with their digital counterparts using desk-mounted scanners which capture modifications added by the users.

Paper-Augmented Digital Documents [Guimbretiere, 2003] use a special pen to record all the annotations made on paper documents and allow users to synchronize them with their original digital version. This is made possible by the Anoto technology [3], which prints unique patterns invisible to the human eye on paper sheets. These patterns are detected by a special pen that stores information about the page that is edited and a specific position within it. The approach is however limited since it requires a new architecture, namely printers able to add the Anoto patterns to documents and pens that are able to read them.

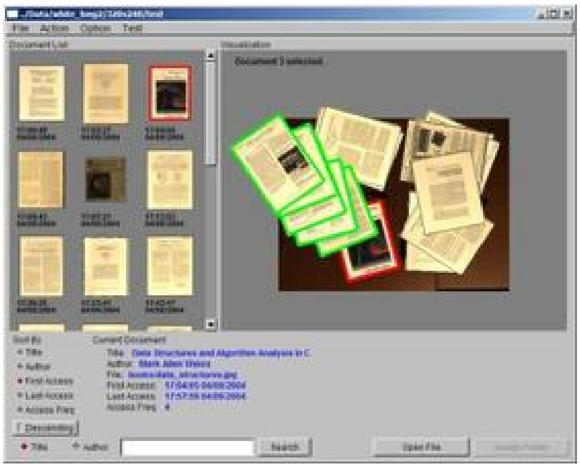


Figure 3.3: Snapshot of the desktop application of the video-based document tracking proposed by [Kim et al., 2004]. It allows users to browse through the stacks of documents placed on an office desk.

[3] http://www.anoto.com

Figure 3.4: The command bar printed on each document in the system proposed by Smith et al. [Smith et al., 2006]. It allows users to issue commands by hiding the corresponding icon.

3.1.2 Tracking paper documents on physical desks

Several systems have been developed to track the position of paper documents on a physical desk to help users find them when needed.

Kim et al. [Kim et al., 2004] proposed a system that constantly monitors an office desk, using a camera to track stacks of documents. The system recognizes the documents and links them with their digital version. A desktop application lets users browse through the documents detected on their desk, using several techniques like visual query through thumbnails of the documents, keywords search, sort or even remote desktop connections (Figure 3.3).

A similar approach has been taken by Smith et al. [Smith et al., 2006], also based on computer vision techniques but using special markers to recognize and track the position of documents stacked on a desk. An interesting feature of the system is a command bar, printed on each document, which allows users to issue commands on the document like annotate, e-mail or link (Figure 3.4).

3.1.3 Adding multimedia content to paper documents

Another line of research explores the possibility to add multimedia content to paper documents, including sound recordings or video.

The Audio notebook [Stifelman, 1996] synchronizes users' handwritten notes with an audio recording of the surrounding sounds when the annotations are written, during a lecture or a meeting for instance. The system uses a digitizing table to capture notes. The recording can then be played back by placing the pen on printed buttons or by pointing at a specific location on the page, starting the playback at the time where the corresponding notes were taken.

A user study conducted by West et al. showed that a common memory aid among elders is a photo album or a scrapbook in which items are collected and preserved [West et al., 2007]. They proposed a system called Memento which supports the creation of a scrapbook website by interacting with a real book. Using Anoto technology, it allows users to add not only pictures and written annotations but also multimedia content like audio annotations, digital pictures and video (Figure 3.5).

Figure 3.5: Pictures of a page created with Memento [West et al., 2007], a system that supports the creation of scrapbooks (common memory aid among elders) from a real book. Top: the page in a web browser. Bottom: the original page as created in the scrapbook.

3.2 Paper as an interface to computer applications

A few systems use paper as an interface to control software applications. Compared to examples described in the previous section which aim at augmenting paper documents and where interactions with their content is the goal of the system, they take advantage of paper for its physical affordances, replacing other interfaces such as the mouse or the keyboard.

Palette [Nelson et al., 1999] allows presenters to control slideshows through a set of index cards. Each card is printed with a thumbnail of the corresponding slide, text notes and a machine-readable marker. Slides are shown by sliding a card below a reader placed on the presentation table (Figure 3.6). User studies have shown that the system allows to start a presentation immediately, without waiting

Figure 3.6: Elements of the Palette system [Nelson et al., 1999], which allows presenters to control slideshows with printed cards. The content of the slide is printed on the corresponding card. To display a slide, users simply show its card to a card reader (top left device).

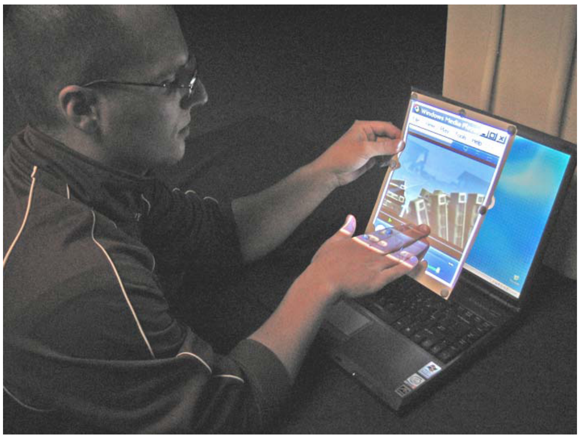


Figure 3.7: A user transferring a computer window on a piece of paper with the PaperWindows system [Holman et al., 2005]. The sheet is tracked thanks to infrared reflectors attached to its borders.

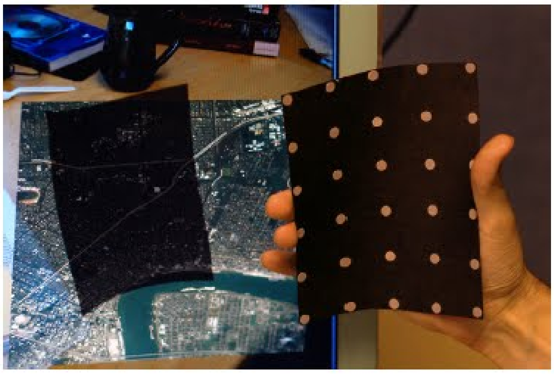


Figure 3.8: The prototype of a foldable user interface proposed by Gallant et al. [Gallant et al., 2008]. The shape of the card stock folded by the user is detected by the system and applied to its digital representation (behind).

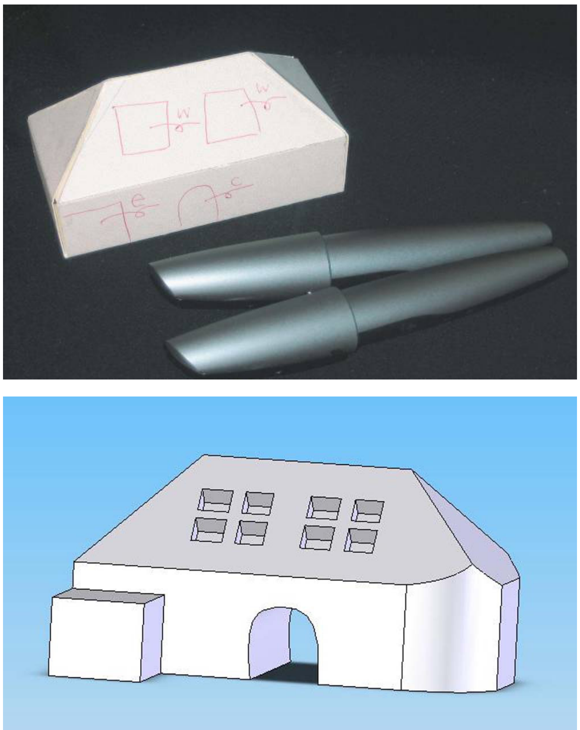


Figure 3.9: Pictures of ModelCraft [Song et al., 2006]: annotations made on paper-based small-scale models (top) are interpreted as 3D drawing commands and applied to the corresponding digital model (bottom).

for the presenter to look for the presentation file as it usually happen. It also allows presenters to jump to any slide without having to scroll through all of them and makes it easy to rearrange the presentation order, beforehand or even during the presentation itself. The authors also argue that the system has an impact on the preparation of presentations by supporting the sharing of slides and discussions about them, as well as note-taking because users can write directly on the cards.

PaperWindows [Holman et al., 2005] is a prototype of digital paper replacing windows of Graphical User Interfaces (GUIs) by sheets of paper. Users can transfer a digital window on a paper sheet by a simple gesture and then interact with its contents (Figure 3.7). Since flexible paper displays are not yet available, the system achieves it by adding Infrared (IR) reflective markers to real paper, tracked using a Vicon Motion Capturing System [4]. The system was developed to explore different interaction styles made possible by paper displays, based on a set of gestures: hold, collocate, collate, flip, rub, staple, point and two-handed pointed. These gestures were used as a basis to implement a set of ten actions, including select, copy & paste, scroll, open&close, ...

Gallant et al. [Gallant et al., 2008] also explored the possibilities promised by future flexible paper displays, focusing on *Foldable User Interfaces*. They implemented a prototype made of card stock paper augmented with infrared reflectors tracked through an IR webcam (Figure 3.8). A set of interaction styles were explored, including hovering, folding, leafing or shaking the card stock to implement actions such selection, browsing or zooming.

ModelCraft [Song et al., 2006] built on the foldable property of paper but with another goal in mind. It allows users, in particular designers and architects in the early stages of a project, to interact with 3D digital objects through physical models made of folded paper. Using the Logitech io2™digital pen [5], it makes it possible to edit the shape of the objects through simple annotations made directly on the physical model (Figure 3.9). To add a door to a house for instance, users draw its shape and sketch a specific command that will result in an extrusion in the digital model.

3.3 Hybrid tangible and paper systems

The literature offers only a few examples of systems based on a mixed approach integrating both tangible artifacts and paper.

PaperButtons [Pedersen et al., 2000] are an extension to the Palette system [Nelson et al., 1999], described in Section 3.2. Buttons were added to original presentation cards as a response to users' requests for additional features and mobility during presentations (Figure 3.10). A user study performed during the design of the prototype showed that tactile guidance and a sensible feedback when pushing buttons are crucial elements. These needs illustrate the potential of hybrid approaches: a

[4] http://www.vicon.com
[5] http://www.logitech.com/

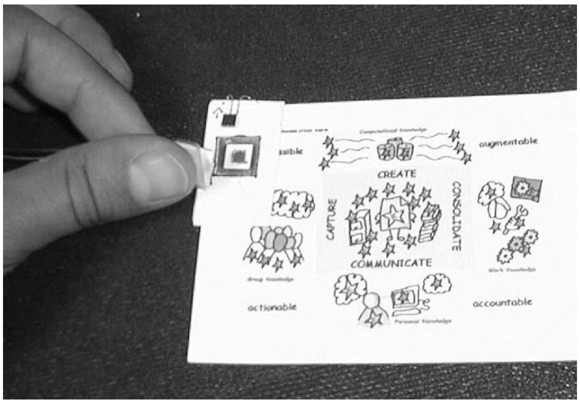


Figure 3.10: A PaperButton [Pedersen et al., 2000] added to a Palette card [Nelson et al., 1999] to support presenters' mobility.

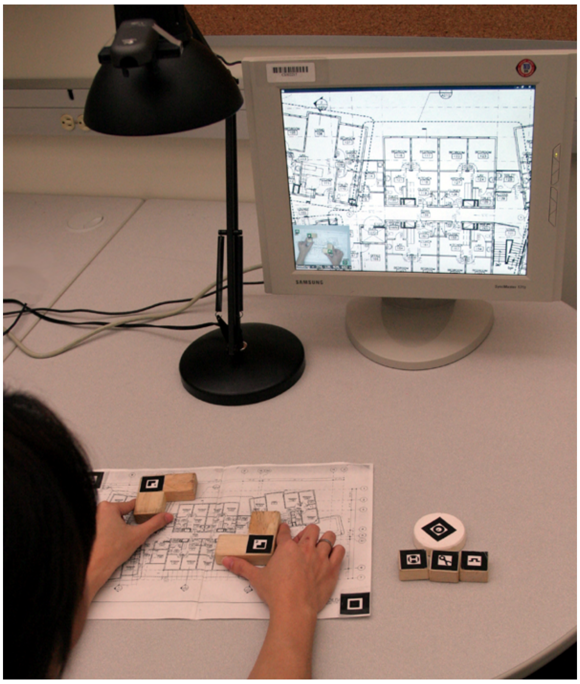


Figure 3.11: A picture of Jump, a *tangible query interfaces* [Terry et al., 2007] for architects. A user selects a region of a document with the *framing tool*.

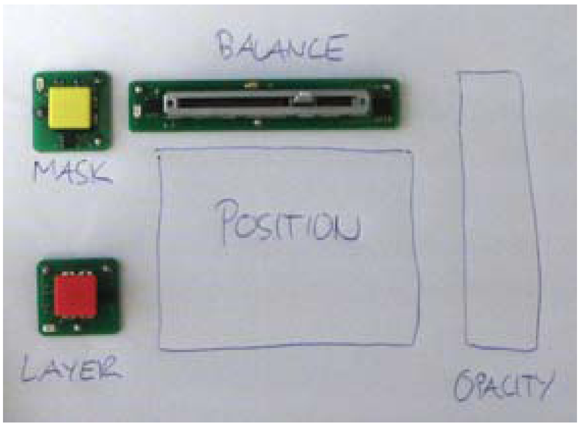


Figure 3.12: A VoodooSketch tablet [Block et al., 2008] made of both physical and sketched controls. Handwritten labels define the functionality attached to each control.

purely paper-based interface based on printed buttons could not provide tactile feedback to users, but physical buttons attached to the presentation cards do it naturally.

Terry et al. proposed the concept of *tangible query interfaces* [Terry et al., 2007]. Their system, Jump, allows architects to obtain more information about a architectural paper document by placing a set of physical objects on top of it. A camera placed above a regular desk recognizes documents and tangible artifacts through visual markers and display additional digital information on a computer screen (Figure 3.11). Visualization tools include a *framing tool* to select a region on the document, *filter tokens* to modify the type of information displayed and a *time machine tool* to access different versions of the document.

VoodooSketch [Block et al., 2008] allows users to bind applications' functionalities to physical or sketched controls. The system consists of a tablet integrating two technologies: Anoto, which captures users' sketches and VoodooIO, which provides a toolkit of physical control devices. Users interact with the tablet by attaching control devices like buttons or sliders to the tablet and bind them to an application by writing a functionality name next to them (Figure 3.12). It is also possible to create controls by simply sketching them and then use pen inputs to control them.

3.4 Augmented paper in education

Paper is ubiquitous in classrooms and it was thus natural for researchers in the field of PUIs to explore new ways to augment these documents with digital information.

Listen Reader [Back et al., 2001] is an interactive story book which is associated with a sound track. RFID tags identify the pages and electric field sensors allow

Figure 3.13: Reading an interactive story book: Listen Reader [Back et al., 2001] sounds react to hands movements above the pages.

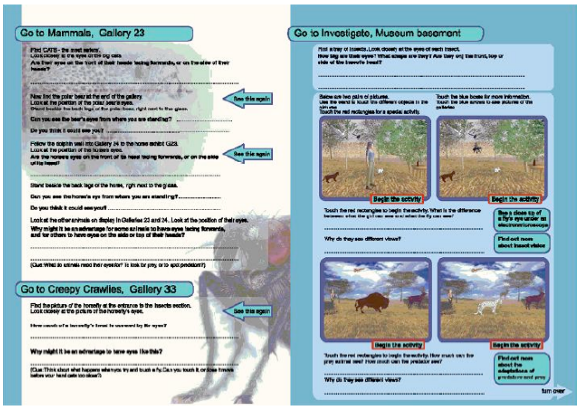


Figure 3.14: A Paper++ worksheet [Luff et al., 2004]: the right page is printed on conductive ink; interactive panels are activated by placing a special pen on top of them and displayed on a computer screen.

children to interact with the sound using their hands. The books were tested in museums and it was observed that visitors spent much more time reading than during a typical museum visits (Figure 3.13). Social reading activities also appeared to be encouraged by the augmented books, with one person often reading aloud to others.

Another example of an augmented book is the MagicBook [Billinghurst et al., 2001] which uses Augmented Reality (AR) techniques to add 3D digital models on top of pages. In this case, users have to wear special glasses called head-mounted displays which integrate digital information to a video track of what users look at.

Paper++ [Luff et al., 2004] was developed to merge digital content with educational paper documents. A technique based on conductive ink and special pen allows users to activate interactive elements of a document (Figure 3.14). The results are presented on a computer screen.

CoScribe [Steimle et al., 2008] supports collaborative annotations on lecture slides for university students. Anoto technology is used to record students' annotations during lessons, which can then be synchronized with a computer and shared with others through a desktop application. Printed buttons on lecture slides allow students to tag their annotations, specifying for example if a note is a question or a comment. Sticky notes also printed with Anoto patterns can be used to define bookmarks in documents, by simply attaching them to a page and making a link gesture with the pen (from the page to the bookmark).

3.5 Open issues

3.5.1 Infrastructure and adoption

As pointed out by [Johnson et al., 1993], one of the main strength of paper lays in its ubiquitous presence in almost every situation of our everyday life and the availability of the necessary infrastructure (pencils, erasers, printers, fax machines, ...). This is also one of the main issues that PUIs are facing, since most of the examples reviewed in this chapter are based on new technologies such as Anoto and alike, which are incompatible with the existing infrastructure. Specific printers are for example needed to print Anoto patterns on paper sheets which otherwise has to be bought beforehand. Users are also forced to use specific pens if they want to take advantage of these technologies. This constitutes a great barrier to their adoption by both organizations and individuals.

A new infrastructure seems to be inevitable if we once want to benefit from the opportunities promised by research on augmented paper documents. This is not necessarily true in other areas of research, in particular when paper is used as an interface to computer applications with users working on a desk. In this case, the existing infrastructure for paper can be kept and be complemented with technologies such as computer vision or scanning devices. This is the case of some of the systems described above, such as [Kim et al., 2004] or [Nelson et al., 1999]. The work presented in this dissertation follows this approach. We observe the implementation of a PUI that takes advantage of the available paper infrastructure in an authentic context.

3.5.2 Opportunities for new investigations

While augmented paper documents have received a lot of interest from the research community, there are few examples of paper used as an interface to computer applications. This is both surprising and disappointing since several works in this field have given interesting results. An example is Palette [Nelson et al., 1999], which illustrated how paper contributes to the creation of flexible and rich interfaces, in that case to control slideshows. It is even more difficult to find examples of works based on hybrid tangible and paper interfaces, which also showed promising results but were not followed by an active and explicit exploration of the opportunities offered by this approach. Mixing paper and tangible artifacts in an interface appears however quite natural. These interaction modalities share a range of common properties, such as being based on physical objects which are intuitively understood by people.

Among the examples introduced in this chapter, PUIs can be broadly separated in two categories: interfaces based on the physical manipulation of paper or paper-like devices (i.e. *foldable interfaces* [Gallant et al., 2008]), and interfaces based on the content of paper documents (e.g. [Johnson et al., 1993, Pedersen et al., 2000]). The first category is easily assimilated to Tangible User Interfaces (TUIs) since it relies on the physical properties of paper, and is thus facing the same issues as pointed out in Section 2.5. The second category has a great potential as a complementary interface to TUIs and, as this dissertation is highlighting it, as a solution to their scalability issue. These interfaces, which we refer to as Interactive Paper Forms (IPFs), build on another property of paper which is to be a universal support for information. These interfaces give a particular meaning to each sheet of paper based on its printed content. With the exception of *foldable interfaces*, physical properties of paper sheets are usually not directly used as input to the computer system. Stacking, folding or bending pages does not have an effect on the application. The interaction is rather based on the content of the document, like in the Palette system [Nelson et al., 1999], when only the content of each card is important to select a slide to display. Any physical action on the card itself does not have any impact on the slideshow. The physical properties of paper documents are nonetheless central to the richness of these interfaces, but in an indirect way. They build on the habits people have developed while working with paper documents, using for example stacks to save space, relying on spatial memory to retrieve them and many other strategies that make the use of paper as an interface so natural. The physical properties of paper documents are thus useful for the *management* of the interface, more specifically for helping people to navigate through the available content. Interactive paper forms such as Palette [Nelson et al., 1999] or the cover sheets used in the XAX server [Johnson et al., 1993] offer a set of generic controls (e.g. check boxes, sliders or buttons) that allow them to give access to an unlimited set of options and parameters and thus make them perfect candidates to address the scalability issue of TUIs.

Chapter 4

Research Questions and Method

EVEN though Tangible User Interfaces (TUIs) and Paper User Interfaces (PUIs) follow a similar approach based on the use of everyday objects as interfaces (physical artifacts and paper documents), they surprisingly followed rather independent and parallel research paths. As we have seen in Section 3.5, only a handful of systems tried to bring these two interaction modalities together and take advantage of their specific properties.

We propose the use of PUIs as a way to overcome the scalability issue of TUIs. As we have seen in Chapter 2, TUIs rely on the rich physical affordances of tangible artifacts to offer a strong coupling between the real and the digital worlds. Manipulations of task-specific tangible artifacts are mapped onto actions in the digital space and give users the impression to be directly interacting with the virtual objects. While the specificity of the interface is at the core of the richness of TUIs, it makes it difficult for those environments to cope with functionality-rich applications. The use of specific objects limits their scalability since only a restricted number of interactive devices can be practically handled by users before the complexity of the interface exceeds its advantages.

This chapter introduces the concept of Tangible and Paper Environments (TaPEs) which builds on these two interaction modalities to provide users with both intuitive and scalable interfaces. A specialized TUI brings direct manipulation of digital objects through the rich physical affordances of domain-specific artifacts. Interactive Paper Forms (IPFs) offer scalability through a set of generic interaction primitives. The resulting interface provides nonetheless a consistent interaction modality thanks to the shared physical nature of its paper and tangible components.

We propose a model that describes the affordances and the impact of TaPEs at different levels of interaction. It considers three interaction circles: the individual users, groups and the surrounding context. This model is based on the assumption that TUIs and PUIs have complementary affordances that do not provide the same value at each level: physical artifacts offer a richer and more direct interaction modality than IPFs at the individual level but the affordances of paper play a unique role from the perspective of the integration of the system in its context. At the group level, the shared physical nature of these two interaction modalities offers a consistent collaborative interface to the users.

The main objective of this dissertation is to assess the complementarity of tangible and paper components in a TaPE. Three main research questions aim to evaluate the complementarity of these two interaction modalities at the different levels proposed by our model of TaPEs. These questions are presented during the description of the model in Section 4.2.

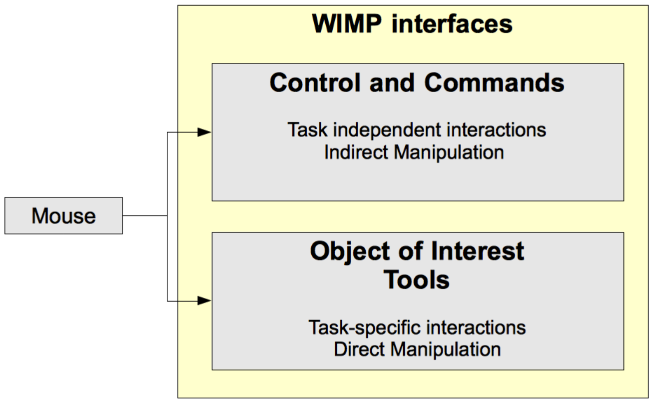


Figure 4.1: The two types or interface elements of WIMP interfaces: task-specific OoI and DM tools, and secondary interface elements for task-independent controls and commands. Both types are controlled by a unique input device, the mouse.

4.1 Tangible and Paper Environments

TaPEs are built on the same structure as WIMP interfaces, with two levels comprising the OoI and DM tools on one hand, and commands and controls on the other hand. The difference lays in the way users interact with these two levels. WIMP provide users with a unique interaction modality, a mouse, which is used to act on both levels through a limited set of possible actions such as clicks and *drag&drop* gestures (Figure 4.1). As shown on Figure 4.2, we propose to break these two levels among different interfaces: tangible artifacts to represent the OoI and DM tools, and IPFs to handle controls and commands. The objective is two-fold: support rich and engaging user experiences with the core aspects of an application thanks to domain-specific physical objects and address the scalability issues of TUIs by building on a set of generic interaction primitives that can easily handle a large number of controls and commands distributed over a set paper sheets. We now give a more detailed description of the purpose of each interaction modality.

4.1.1 Tangible artifacts

Tangible artifacts bring the richness and the representational power of domain-specific objects to each application. Our model proposes to limit their use to the

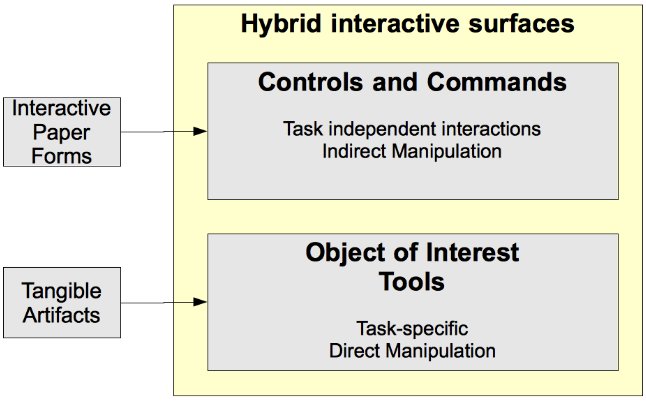


Figure 4.2: The hybrid model we propose, based on Tangible User Interfaces to interact with the Object of Interest and Interactive Paper Forms to handle parameters and options.

aspects of an application where their unique affordances are the most valuable, namely the OoI and DM tools which focus most of the users' attention. As we have seen during the review of relevant work from the literature on TUIs in Chapter 2, in particular in the field of interactive surfaces, they almost exclusively address these aspects of an interface. Examples of tangible artifacts representing the OoI include the small-scale models of buildings used in URP [Underkoffler and Ishii, 1999], the bus stops placed by users in the EDC environment [Arias et al., 1997], the continuous landscape in Illuminating Clay [Piper et al., 2002] or the telephone cellular towers in the system based on mechanical constraints described by [Patten and Ishii, 2007]. DM tools are illustrated by the physical pucks used on the SenseTable [Patten et al., 2001], the tools used to change buildings' surfaces or modify the wind's direction in URP [Underkoffler and Ishii, 1999] or rubber bands used as constraints in [Patten and Ishii, 2007].

4.1.2 Interactive Paper Forms

We introduced the term Interactive Paper Forms in Section 3.5 to describe PUIs which use paper for its quality as a universal support for information. More formally, we define an IPF as a user interface to a computer application which associates a set of interaction primitives, taking the form of printed information, to commands and/or controls of the application. Interaction primitives include input and output elements used to issue commands and display numerical or graphical information. Figure 4.1.1 shows an example of such an interface, called TinkerSheets, which we developed to test the model presented here in real situations. The information printed on the page includes static (textual descriptions) and interactive (radio buttons, sliders and display zone) content. In this particular example, users issue commands by placing tokens on the input areas and Augmented Reality (AR) techniques are used to display information. Any other type of technology could be used to implement an IPF interface, such as Anoto

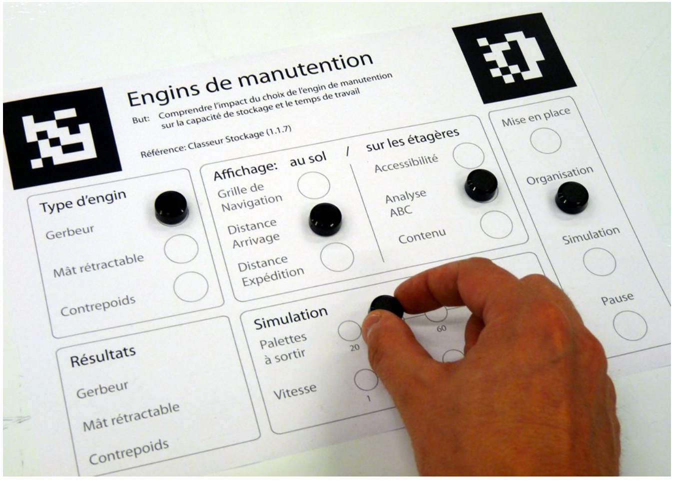


Figure 4.3: An example of a TinkerSheet, our implementation of an Interactive Paper Forms interface, with a user setting a parameter using a physical token.

	Indirection	Integration	Compatibility
Tangible artifacts	+ +	+ +	+ +
Interactive Paper Forms			
- activation	+ -	+ +	+ +
- organization	+	+ +	+ +
- action	-	+ -	-

Table 4.1: Comparison of TaPEs interaction elements using properties defined by Instrumental Interaction.

[1] (see Chapter 3). A more detailed description of TinkerSheets is given in Section 6.3.

IPFs are the physical equivalent of peripheral interface elements used in WIMP interfaces. Individual items (i.e. commands) are laid out on sheets of paper and users navigate through them to find the feature they need. IPFs interfaces can thus handle functionality-rich applications by using as many forms as necessary to cover the full set of available commands and controls. Their paper nature allows them to be manageable by users because they can be organized in folders or even books for very large applications. In the same way as peripheral interface elements break DM principles to offer a large set of functionalities, IPFs do not offer the same level of directness as tangible artifacts but bring scalability to TaPEs. Compared to a TUI, they greatly limit the development costs by relying on a standard set of reusable interaction primitives.

[1] http://www.anoto.com

4.1.3 Analysis of TaPEs using the Instrumental Interaction model

The analysis shows that TUIs offer high degrees of indirection, integration and compatibility [Beaudouin-Lafon, 2000]. For instance, the small-scale models of buildings used in URP [Underkoffler and Ishii, 1999] represent domain objects that are directly manipulated by users (indirection), offer even more Degrees Of Freedom (DOFs) than their digital counterparts since users can manipulate the physical models in 3 dimensions but the digital model considers only 2D positions (integration), and digital objects are tightly coupled with the tangible models (compatibility).

The situation is more complex for IPFs. They are meta-instruments, similar in this sense to menus in WIMP interfaces, but their nature tend to change depending on whether users interact with them or the instruments they contain. We can distinguish the following interaction patterns, summarized in Table 4.1:

Activation takes place when the form which contains a needed feature is not directly visible. The reason might be that it has not been used yet, is below a stack of other forms or has been put aside. Users then have to switch their attention to a physical search task where the OoI is the IPF on which the feature is located. This task is facilitated if the forms are organized in some logical way or if users remember where they left it the last time they used it. If the form is used for the first time, this situation is comparable to the navigation in a menu in a WIMP interface: users have to somehow know the organization of sub-menus to find the command they need in a faster way. When a form has been used already and is either stacked or set aside, the situation is more similar to the case of property boxes. Users usually remember where they are or can use visual clues to find them quickly. Bringing IPFs to the forefront has a relatively low degree of spatial indirection but their physical nature offer higher degrees of integration and compatibility since users directly manipulate them.

Organization arises when users wish to have access to several commands or feedbacks located on different IPFs. These forms become like domain objects that users manipulate directly and arrange on the interactive surface. This interaction pattern can be compared to the use of window titles in WIMP interfaces: it offers high degrees of indirectness, integration and compatibility. It is assimilable to a TUI in this case because users manipulate a tangible instance of these (temporary) domain objects.

Action corresponds to situations where users use tokens or pencils to issue a command. IPFs can be related in this case to property boxes of WIMP interfaces. If the form is already available, users do not have to go through the activation pattern and thus experience a small spatial offset (low degree of indirection). The degrees of integration and compatibility depend on the nature of the command and the type of interface elements available on a particular implementation of IPFs. Setting a numerical value by writing it offers a lower degree of compatibility than placing a tangible token on the element and turning it to increase or decrease the value.

This analysis shows that IPFs do not offer the same level of indirectness, integration and compatibility than a TUI does. While TUIs build on rich physical affordances of task-specific artifacts to provide users with high degrees of indirectness, integration and compatibility, IPFs suffer from a higher degree of indirectness and are thus closer to menus in WIMP interfaces. This is the result of a trade-off between directness and scalability: IPFs allow tangible environments to handle functionality-rich applications at the cost of a less direct interaction modality.

If we consider the *activation* and *organization* interaction patterns, some advantages of the paper modality become visible. In these cases, IPFs are the focus of the interaction: they become temporary domain objects and users benefit from the affordances of paper documents to navigate through the available forms and spatially arrange them on the interactive surface. Their physical nature allows users to stack them and save space on the interactive surface. Thanks to their printed content, they are persistent and continue to exist even when they are out of the interactive area: users can rely on visual cues to search faster through a stack of forms or spatially arrange them to facilitate their retrieval.

To sum up, IPFs bring a solution to the scalability issue of tangible environments but at the cost of a less direct interaction modality that forces users to temporarily switch their attention from the domain object (TUI) to secondary interface elements. Issuing a command using a paper form offers a level of indirection similar to a menu in WIMP interfaces, but the physical nature of paper gives a certain advantage to IPFs compared to other approaches.

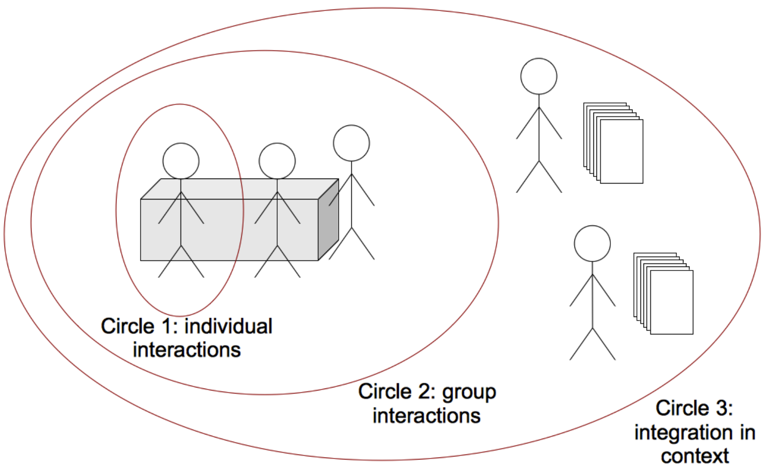


Figure 4.4: The three interaction circles concerned with TaPEs.

4.2 Model and research questions

A model for TaPEs should recognize the fact that paper and tangible interaction modalities have an impact not only at the individual user level but also play an important role at the group level and in terms of the integration of the digital environment in its surrounding context. We propose a descriptive model of TaPEs organized in three interaction circles (Figure 4.4) which emphasize the particular nature of Paper and Tangible User Interfaces. The overview and analysis of TaPEs given in the previous sections was mainly concerned with the individual level, showing how IPFs can be used in combination with a TUI to bring scalability to a tangible environment. A model focusing on this level of interaction would miss a fundamental aspect of these environments, naturally adapted to collaborative settings. The potential of the combination of these two interaction modalities should thus be considered. The integration of tabletop environments in their context of use is also a crucial aspect. IPFs may offer the opportunity to create a stronger connection between the environment and surrounding offline activities, in particular in paper-centric contexts.

The model emphasizes the complementarity of IPFs and TUIs. While these interfaces share a set of common properties, such as their physicality, they also offer specific affordances that we argue bring unique benefits at each level of interaction. These differences are illustrated in our model, as shown on Figure 4.5. The TUI plays a central role at the individual level since it offers rich physical affordances to users who directly manipulate the OoI. At this level, we expect that the specific properties of IPFs will not offer the same level of directness, an assumption supported by the analysis presented in Section 4.1.3. The situation is different at the group level, where the shared properties of paper and tangible artifacts are expected to offer a consistent interaction modality that is particularly well adapted to collaborative situations. At the context level, the unique affordances of paper should support seamless transitions between the tangible environment and surrounding offline activities. The interface can potentially be integrated in the existing paper-based practices and thus reduce the distance between online and offline situations.

The complementarity of tangible and paper components of TaPEs and its impact on the different interaction circles is a central aspect of this dissertation. The next sections discuss in more details the three interaction circles and introduce corresponding research questions.

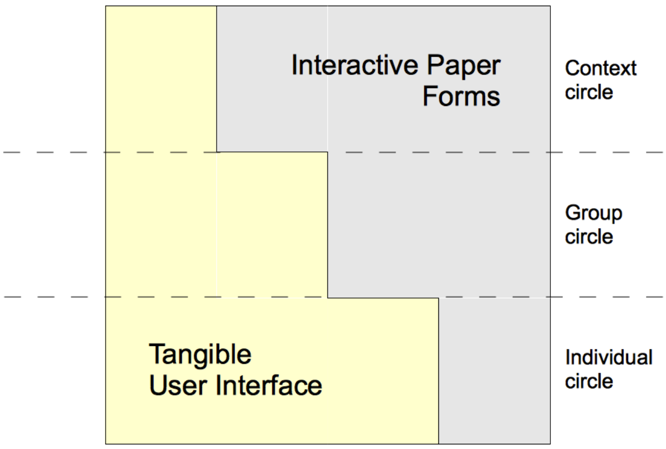


Figure 4.5: Complementarity of tangible and paper components of TaPEs in three interaction circles.

4.2.1 Question 1: Individual interactions

The first research question is concerned with the impact of the combination of paper and tangible components on the interactions in the individual circle.

Research question 1

What is the complementarity of tangible and paper interactions in a tabletop environment?

This question aims at evaluating the benefits and drawbacks related to the use of two different interaction modalities within a TaPE. As illustrated by the analysis of TaPEs with the Instrumental Interaction model [Beaudouin-Lafon, 2000], IPFs offer different degrees of indirectness depending on three types of interactions: activation and organization offer average degrees of indirectness but user actions have a low degree of indirectness and may thus have a negative impact on the quality of interactions. We expect that the impact of less direct interactions on IPFs will have a limited effect because of the distribution of features among the paper and tangible components of the interface. Our model of TaPEs proposes to map core aspects of applications such as the OoI and Direct Manipulation (DM) tools onto tangible artifacts and secondary interface elements onto IPFs. Our hypothesis is that peripheral elements usually involve relatively discrete and short user interactions that decrease the negative effects of an indirect interaction modality.

4.2.2 Question 2: Group interactions

The second research question is concerned with the complementarity of tangible and paper components of a TaPE in the group interactions circle. In this circle, the fact that both interfaces rely on physical objects, task-specific artifacts for the TUI and paper sheets for IPFs is expected to play a crucial role.

Research question 2

How does a TaPE impact group interactions during collaborative problem-solving activities?

Going back to the analysis performed with the Instrumental Interaction model, this second circle is more about the way activation and organization take place rather than the actual actions of single users on a sheet. From this perspective, paper and tangible artifacts are strongly similar. They are *visible*, in the sense that each team member can see what the others are doing. Moving a tangible or changing a parameter on an IPF is done through a physical movement which takes place directly on the interface element; the intentions of a user are to a certain level predictable and can then be interrupted by other team members whenever necessary. This is not the case for instance in WIMP interfaces, since interactions are mediated through indirect and almost imperceptible movements of a mouse. We thus hypothesize that collaboration is naturally supported by both paper and tangible interaction modalities because no user gets an exclusive control of the system. A tangible just placed by a user or a parameter set on a form can be modified by any other member of the group. This is not the case again in most mediated interfaces such as Graphical User Interfaces (GUIs) where only the user who controls the mouse can act on the system.

We also expect IPFs to offer some advantages because of their paper nature, which allows users to handle them as they would do with standard paper documents. This includes sharing documents (user A physically passes a document to user B), changing their orientation to make them readable for others or assigning roles by giving different forms to each group member.

4.2.3 Question 3: Context integration

Research question 3

How does a TaPE integrate in a classroom ecosystem?

IPFs can have an important impact on the integration of a tangible environment in its surrounding context, thanks to the unique affordances of paper. It is difficult at this stage to establish general rules because each context will have particular needs and benefit in a different way from a PUI. It seems nonetheless reasonable to assume that environments relying heavily on paper in their daily activities will be able to take the most advantages from TaPEs. We expect that the following possibilities offered by IPFs will play an important role at this level:

Integration into existing documents. Thanks to their paper nature, IPFs can be handled like regular documents and actually merged with pre-existing, non-interactive documents.

Integration into existing practices. A paper interface allows users to engage into interactive activities in the same way they would do with traditional pencil and paper tools. The integration of IPFs into existing documents reduces the gap between digital and offline activities and contributes to make the workflow of digital activities visible with the physical movements of IPFs from one person to the other.

Transfer of data through annotations. Annotations can be a powerful tool to support seamless transitions between online and offline tasks. When users want to reuse some data displayed on an IPF, they can simply recopy it directly on the form and thus make it available outside of the interactive system.

This dissertation addresses the case of classrooms, which are a good example of a paper-centric context. The learning material is usually printed in books, additional material is distributed on photocopies, and exercises and exams are almost exclusively done on paper. We study in particular the way IPFs support orchestration, i.e. the organization of activities in a classroom by teachers.

4.3 Method

The research questions addressed in this dissertation, raised in particular by our model for TaPEs presented in Section 4.2 can not be answered by purely controlled experimental studies. This is why we followed a Design-based Research (DBR) approach, a method developed in the field of the learning sciences which emphasizes evaluations of learning environments in their actual context of use. The main characteristics of Design-based Research are summarized by the DBR collective in the following way:

- the central goals of designing learning environments and developing theories or *prototheories* of learning are intertwined;
- development and research take place through continuous cycles of design, enactment, analysis, and redesign (Cobb, 2001; Collins, 1992);
- research on designs must lead to sharable theories that help communicate relevant implications to practitioners and other educational designers (cf. Brophy, 2002);
- research must account for how designs function in authentic settings. It must not only document success or failure but also focus on interactions that refine our understanding of the learning issues involved;
- the development of such accounts relies on methods that can document and connect processes of enactment to outcomes of interest.

DBR recognizes the important role that context plays on the efficiency of a system and argues that the complexity of an authentic setting can not be captured by controlled experiments. The approach does not focus exclusively on the design of artifacts but tends to go towards less concrete aspects such as activity structures, institutions, scaffolds and curricula [Collective, 2003]. It encourages the active participation of practitioners to the development of the learning environment and fosters regular observations in authentic settings. The design is not meant to be stable during observations but should constantly evolve through the data collected in the field. A good comparison of controlled psychological experiments and a DBR approach is given by [Barab and Squire, 2004] along the following seven categories:

Location of research: in a laboratory *vs.* real-life setting where most learning actually occurs;

Complexity of variables: few dependent variables *vs.* multiple dependent variables;

Focus of research: identifying a few variables and holding them constant *vs.* characterizing the situation in all its complexity, most of it is not known *a priori*;

Procedures: fixed *vs.* flexible design revision based on success in practice;

Amount of social interaction: isolated learners *vs.* complex social interactions;

Findings: focus on testing hypothesis *vs.* looking at multiple aspects of the design and developing a profile that characterizes the design in practice;

Role of participants: participants as subjects *vs.* participants involved in the design.

These categories are useful to understand why DBR is a research method adapted to the questions addressed by this dissertation. The potential of TaPEs in terms of integration in their context, more precisely in a classroom, can not be assessed in an experimental setting. The evaluation has to take place in an authentic context to bring valid results. The nature of the question makes it impossible to be reduced to a single variable and it benefits from an account of observations conducted with the system that considers the complexity of the situation. Our work involves a large part of design, which makes it difficult to state precise hypotheses beforehand and stick to a fixed environment: a more complete picture of the variables involved can be obtained by redesigning the system according to the observations conducted in the context of use. The social interactions are naturally rich since they involve not only groups of learners but their teachers as well, who participated to the design of the environment.

The DBR approach is nonetheless the target of several criticisms, in particular regarding the generalizability of the results, made difficult because of the complexity of the situations where they are gathered. To overcome this inherent limitation of DBR, we adopted a mixed approach and combined field studies with more formal experiments that assessed particular aspects of the design in a controlled, laboratory context.

Chapter 5

Context and specific research questions

In line with the Design-based Research (DBR) principles outlined in Section 4.3, our model for Tangible and Paper Environment (TaPE) and the associated research questions have been assessed in the authentic context of vocational training in logistics. We worked in close relationship with two teachers and developed a TaPE, the Tinker Environment (see Chapter 6), which aims at supporting apprentices' understanding of logistics concepts at school. The system has been tested on a regular basis in different professional schools by four teachers.

The development of the Tinker Environment in this particular context allowed us to address the issue discussed in Section 2.5.2 regarding the use of Tangible User Interfaces (TUIs) in learning situations. We propose a pedagogical approach which takes advantage of another aspect of the complementarity of paper and tangible components, which is to display information at different levels of representation. The task-specific artifacts of the TUI are used to offer a concrete representation to learners while the paper nature of Interactive Paper Forms (IPFs) allows them to present information at a more abstract level. Our hypothesis is that these two levels of representation can be used to prevent learners from being stuck in a concrete mode of reasoning as it may happen with tangible artifacts.

This chapter starts with a description of the vocational training in logistics through a field study we conducted in schools and companies and which led to the identification of a central issue faced by apprentices in logistics, the abstraction gap. We then propose a solution to this issue, explain how TaPEs may help to solve it and introduce the corresponding specific research questions.

5.1 Context

The work reported in this dissertation took place in the context of the Swiss vocational education and training system, which is mostly organized as a dual system. This means that apprentices go to a school one day per week and spend the rest of the time working in a company. In professional schools, apprentices learn both theoretical aspects of their profession and general knowledge in other topics such as mathematics, language and book keeping. Vocational training has a strong importance in Switzerland because two-third of the young adults choose it after obligatory schooling. It thus benefits from a higher status than in other countries where it is sometimes considered as the way for those who do not perform well at school. An apprenticeship typically lasts between three and four years and apprentices are evaluated on their achievements both at school and at the workplace. The dual approach has the advantage to let apprentices learn their trade in an authentic setting. This practical experience is also beneficial for the complementary theoretical knowledge acquired at schools: apprentices can refer to their practice when they are presented with new concepts. Companies also benefit from the dual system through the apprentices' work but also because training apprentices allows them to ensure that enough skilled people will be available in the future [Mühlemann and Wolter, 2007].

The dual vocational training system appears to be a perfect combination of two worlds. An authentic setting on one side, allowing apprentices to develop their skills next to experienced colleagues, and school on the other side, bringing conceptual knowledge and structure to practical knowledge through theory. Our hypothesis was that this perfect picture might not easily happen, since the two different contexts where apprentices are trained raise some challenges related to the articulation of theory and practice. Our objective was to first identify potential problems by observing apprentices at school and at their workplace, and if we found any, develop learning technologies that could help address them.

5.1.1 Apprenticeship in logistics

Young people who enter the vocational training system in Switzerland can choose among more than 200 professions, including office clerks, cooks, electricians, carpenters or dental care assistants. We decided to work with logisticians, who usually work in a warehouse where they take care of reception, storage and expedition of goods. The main criteria that motivated this choice was to avoid professions where workers spend most of their time seating at a desk and working on a computer, which are too close to situations typically addressed by traditional learning technologies developed for college or university students. Our goal was to address issues specific to the vocational training system, which we thought would be more salient in professions involving work away from a desk. This is the case of logisticians, who spend most of their time moving goods in the warehouse or sorting items in the reception area. This apprenticeship is actually divided between three specialities: storage, transport and distribution. Apprentices are supposed to be able to work in any of these specialities at the end of their training but they get more courses on the speciality that corresponds the best to their work at their company. We decided to focus on the storage option since it concerns the great majority of apprentices in logistics.

The apprenticeship in logistics lasts three years. A third partner, the professional association, complements schools and companies by organizing specific courses several weeks per year. Since logistics is a large field using a wide array of technologies and companies of any size and storing many different types of products hire apprentices, most of them are not big enough or are too specialized to give the opportunity to their apprentices to practice each aspect of their trade. These courses, called inter-companies courses, aim at ensuring that apprentices all develop the basic practical skills of a logistician. Forklift driving licenses are also obtained during these courses.

5.1.2 Field study

In order to better understand the work of logisticians and observe the daily life of an apprentice in different contexts, our first efforts were dedicated to a field study. We visited twelve companies, spent three days in a professional school and observed an inter-companies course during two days. We also interviewed teachers, apprentices and their supervisors in their company. We now report on our observations, limited to schools and companies where the most relevant aspects have been observed.

Observations at school

We spent three consecutive days at Centre Professionel du Nord Vaudois (CPNV) (Yverdon, Switzerland), a professional school in the area of our university. We did most of the observations in the classroom of two logistics teachers but also spent some time in a general knowledge course given by another teacher. Breaks and lunch-time were occasions to conduct informal interviews with teachers. We also got access to the course material which gave us a complete overview of the curriculum.

Classroom observations Teaching is done in a traditional way; teachers stand in front of the class and present theory to relatively passive apprentices. Teachers follow the official curriculum, which is developed by the professional association for logistics teaching (SVBL/ASFL)[1] and is the same for all the professional schools. Each topic covered by this material is accompanied by a set of practical exercises done during the class. The two teachers we observed have a solid experience in logistics since they both spent many years working in the industry before teaching at the professional school. This allows them to illustrate the rather theoretical concepts they present during their classes with concrete examples taken from practice.

Curriculum The curriculum specific to logistics can be summarized in three modules: driver, designer and manager. This classification is not official and does not appear in the material but we apply it here for convenience. It organizes the topics according to their degree of difficulty for apprentices and will be useful to relate the curriculum to the tasks assigned to them at the workplace.

The *driver level* corresponds to the basic operations performed by employees doing practical work in a warehouse. It is mainly dedicated to the different types of tools used to move and store goods. These include forklifts, cranes, treadmills, shelving

[1] http://www.asfl.ch

systems, … Apprentices should know that these tools exist and be aware of the safety rules that apply to them (e.g. how to lift a weight with a crane in a secure way). This module also includes the special types of goods that logisticians have to handle during their job (chemical and flammable products), and the specific treatments that have to be applied. Another important topic is the procedures that logisticians have to follow in typical situations like reception and expedition of goods: some forms have to be checked and filled, movements might have to be manually entered in a computer, …

The *designer level* addresses the spatial organization of a warehouse. Compared to the driver module which mainly concerns factual knowledge, this module introduces topics related with the trade-offs made in a warehouse between storage capacity and work efficiency. It includes concepts which have to be taken into account when designing the layout of a warehouse, like the alley width, which depends on the type of forklift used, or raw and storage surfaces, which define the usage ratio, an important measure of storage efficiency. Other important topics are the way goods are stored in the warehouse (e.g. goods with the highest movement rates are stored closer to the expedition dock) and the organization of the work (e.g. predefined picking path through the warehouse for all the employees).

The *manager level* is dedicated to inventory management and economic aspects, i.e. all the decisions that have to be taken about which quantity of each product has to be ordered and when. The goal for the person responsible for this task is to ensure that goods are available when customers order them but at the same time keep the inventory level as low as possible to reduce costs. Even though this module is the most difficult of the curriculum of logisticians, it still only touches upon this complex aspect of warehouse management. A simple model is presented in the curriculum, which makes the strong assumption that demand is constant to define an optimal order size for a given product. It is important to understand that the apprenticeship in logistics does not aim at training experts of supply chain management, able to understand and apply the latest research results in operations research. It is however important for a warehouse employee to understand basic principles of inventory management, which are often enough in small companies and situations where uncertainty is not too high. In this respect it is interesting to note that the equation presented to apprentices, the Andler formula, is derived from the Economic Order Quantity (EOQ) model introduced in [Harris, 1913] and later popularized by [Wilson, 1934]. The EOQ is quite simple but is still useful in many practical situations and is, together with the news vendor model (see [Porteus, 2002]), the basis on which many more complex models are built, addressing for example situations including stochastic demand [Heyman and Sobel, 1990] or multi-echelon systems [Axsater, 2000, Clark and Scarf, 1960]. The Andler formula defines the optimal reorder quantity for a given product type as $Q_{opt} = \sqrt{\frac{200 \cdot M \cdot B}{P \cdot L}}$, where M is the annual customer demand, B are the fixed reorder cost, P is the unit price of the product and L are the storage costs (usually defined as 20% of the total price). The formula computes an optimal trade-off between reorder and storage costs: large reorder quantities lead to fewer reorders but larger storage costs while smaller reorder quantities decrease the amount of products to store but augment the frequency of reorders (reorder costs).

Figure 5.1: Patrick Jermann (left) and an apprentice during a company visit.

Observations at companies

We visited a dozen of companies hiring apprentices in logistics in the french part of Switzerland (Figure 5.1). The selection of companies was done by first asking teachers for their contacts in the industry. Asking the teachers was a good way to get accepted by the companies. We later changed our selection process because we suspected that teachers had good relationships with companies taking special care of their apprentices and offering them a rich training environment. After a few visits we thus chose companies based on more objective criteria like size or type of goods stored, with the objective to complete our picture of the different contexts where apprentices work. Only one of the companies we contacted rejected our demand. We discovered that logisticians are involved in a great variety of companies, from local spare parts retailers to big factories employing thousands of people. We had the opportunity to observe the work of apprentices in very different contexts, in companies handling many kinds of goods, including construction materials, spare parts for industrial machines, toys and wine.

Format of the visits During the first three visits, we applied a technique inspired by *shadowing* [McDonald, 2005], borrowed from ethnography, which consists of observing people performing their normal tasks. As opposed to self-reported observations, where people have to write a log or diary of their activities, shadowing allows researchers to get a direct observation which is not biased by the subjectivity of the participants. We spent half a day in each company, staying as much as possible out of the way of the apprentices. We sometimes interrupted them to ask some questions about an interesting event, to understand what happened or to know whether they faced some difficulties. Following an apprentice during half a day proved to be useful to get a first glimpse into the world of logistics and get some feeling on the typical problems that are encountered and on the type of activities that are assigned to apprentices.

After these initial observations we decided to organize our visits in a different way, for several reasons. First, the apprentices we observed used to perform relatively repetitive activities, such that after a couple of hours we had the impression to understand enough of their job for our purpose. Moreover, unexpected events only happen very rarely. The time we spent in each company was not enough to give us a good probability to experience one in real-time. Second, logistics processes in a company are usually divided in several specific areas, like reception, storage and expedition for the most common ones, and logisticians usually go through all of them during their training. We thus had the feeling to get only part of the picture in each company. Third, we were not only interested in the actual work apprentices are doing at their company but also about their understanding of the more global logistics process where they were involved.

The format we adopted for the rest of the visits was to ask apprentices to give us a guided tour of their company. We usually followed the typical flow of goods through the warehouse, from the delivery by a truck or a train, through the reception area where goods are sorted and the storage area where they are stored to the expedition area where customer orders are prepared for their delivery to the next level of the supply chain. At each step we asked the apprentice to explain us what was happening, how the work was done and also what is happening outside of the company: where the goods come from and where they go.

Semi-structured interviews conducted independently with the apprentices and their supervisor concluded each visit. Our goal was to get some information regarding the way both apprentices and supervisors consider school, how they consider the role of the apprentice in the company as well as the main difficulties encountered during the apprenticeship. The results of our observations are reported in the next two sections.

Company type	**Flows**	
	Information	*Physical*
I - Humans only	H	H
II - Computers support humans	H+C	H
III - Computers control humans	C	H
IV - Computers control machines	C	C+H

Table 5.1: The four different types of companies hiring apprentices in logistics and the division of labor between humans and machines.

Taxonomy of companies The twelve company visits we did during the field study highlighted a large variety of work contexts for apprentices in logistics. Companies differ greatly in terms of size and technological level, going from a local storage managed by hand by an employee and an apprentice to a fully automated warehouse where tens of workers drive forklifts and prepare orders for customers. The larger a company, the more advanced storage management techniques and procedures it uses. Logistics can be described as two parallel flows: the *physical flow*, which represents the real goods moving through the supply chain, and the *information flow*, which corresponds to the information about the state of the goods. We observed that technology tends to control the *information flow* which is easier to handle by a computer. We classified the companies that we visited in four categories spanning the range of situations we could observe, from small, low-technology companies where humans handle most of the responsibilities to big, high-tech companies where humans receive orders from computers and are merely needed because they are more precise than a machine to pick small objects. Table 5.1.2 shows a two-dimensional grid that represents these four categories on the vertical axis and the division of labor between humans and machines among the information flow and the physical flow.

Type I companies correspond to small- to medium-sized structures where almost no technology is used. The employees assume all the responsibilities: they take care of both storage management and goods handling. An example of such a company is a mid-size building materials retailer, employing about fifty people. The company is divided in several warehouses, each one dedicated to a specific type of products. We observed a first-year apprentice, working in the bathroom-related parts warehouse with his supervisor. Their job consists in storing delivered goods, preparing customer orders and managing the storage level.

No storage management system is used to maintain information about the location of products and their availability. The logisticians are responsible for the management of the warehouse and thus decide where to store products. Since there is no information system, logisticians retrieve products using their knowledge of the warehouse organization, their memory and some logic. If they look for a standard product, they know where it is usually stored, but for a special order they need to remember where they stored it or try to deduce where their colleague put it. Experience is very important at this step, because they have to know how the warehouse is organized and the common practices in use for storage management. Writing the name of the consumer who ordered a specific product on its packing is also very useful to retrieve it more quickly.

In **Type II companies**, employees are still responsible for most of the tasks, but use computers as tools to retrieve information about the storage. This is the case for instance of a mid-size books distributor we visited during the study. The company is divided into two warehouses: the main one comprises the administrative office and a storage area for everyday activities like reception, order preparation and expedition; the second one is used as a longer-term storage for books available in large quantities or used less frequently. We observed a third-year apprentice working in the main warehouse who gave us a guided tour of the warehouse and explained the way logistics is organized in the company.

Logisticians use a storage management software which indicates for each book title the amount of items available and their location. Several terminals are located in the warehouse and allow the logisticians to get information about books through a text-based search query or by scanning the book's bar code. Whenever a book enters or leaves the warehouse, the information system has to be updated accordingly.

Although it is very easy to get the location of a book from a terminal, logisticians usually do not use it because they remember where most frequently used books are stored. This allows them to spare some time when storing or retrieving books but is sometimes error-prone. Errors occur when the storage location of a given title has changed or when an employee puts a book on the wrong shelf.

The apprentice explained us that the most difficult part of his job was to learn how to move in the warehouse, read the codes and optimize his path. This example shows that experience is also very important in this company. It allows logisticians to achieve their job in a more efficient way. Logisticians are also responsible for the management of the warehouse, and thus decide where to store each book title. The management used to handle this activity before but passed it to the logisticians who work in the warehouse and are thus better qualified to organize it. To sum up, humans still have the control of their job: they organize their tasks and decide how to achieve them.

In **Type III companies**, workers have lost the control of their job. We observed this situation at a food&beverage retailer employing about hundred people. The apprentices' supervisor gave us a guided tour of the company and explained us the different activities carried out by logisticians.

The work in the warehouse is divided in three main activities: reception of goods, customer orders preparation and pick up areas restocking. Products are stored on pallets and laid out on three-staged shelves. The ground stage is reserved for picking activities, while the two upper ones are dedicated to reserves. Each product type, each pallet and each storage location is identified with a bar code, used to identify it in the storage management system. Every action involving a product has to be validated by reading the corresponding bar codes. Each location is also identified with an alpha-numerical code, posted in front of it to allow a visual identification by the workers. The management system controls each movement of boxes within the warehouse. Each forklift is equipped with a barcode reader and a terminal which indicates to the workers which box should be picked up and where they are supposed to store it. Since its action is validating by reading bare-codes which identify positions and products, the system is able to check that no error has been made.

The value of experienced workers is decreased, as it is less useful to perform well. People still have the opportunity to learn where some products are stored, but this information is less interesting because they have lost their independence and have to follow the orders given by the information system. Experience is still useful to move efficiently in the warehouse as experienced workers find the correct shelves more quickly than newcomers, but it is not a crucial advantage.

Type IV companies represent an extreme case, where computers and machines do almost all the job and leave only tasks that can not be automated to humans. The most salient observation we did of such a company was a large factory producing industrial machines. We were given a guided tour of the warehouse carried out by an apprentice. The internal logistics of this company is mainly devoted to the reception, storage and retrieval of spare parts for the production facility. Logistics is divided in several activities, each one under the responsibility of a fixed group of employees. We now describe the typical path of a spare part from its delivery at the warehouse to its dispatch to the production area.

When a truck arrives for delivery, a first group of workers unloads the goods, signs the delivery form and moves the boxes in the warehouse. A number is assigned to each box. A second group of worker uses then this number to retrieve the corresponding order and check that it is complete. The content of the pallet is opened, checked and put on a new box. Most of the goods received are metallic parts, usually accompanied by a technical blueprint that the logistician uses to check the dimensions of the parts. Each part and each box is assigned a bar code for tracking purposes. The boxes are then transferred to another logistician, who checks that their volume is below the constraints of the storage system. The boxes then enter the storage area, which is a completely automatized vertical carrousel, composed of several alleys where cranes handle boxes. This automata is able to store 20,000 boxes and is fully automated. From the humans' point of view, this area functions like a black box. When the production area of the factory needs a part, an automatic order is sent through the information system and the storage automata will automatically pick up a corresponding box and bring it out of the black box where workers will manually pick up the part. A terminal indicates for each box that passes in front of them which parts have to be picked. When they are done, workers validate the operation by reading a bar code and the box automatically goes back to the storage. The parts are stored on new boxes that will finally be brought to the production area.

In this company, most activities are completely managed and performed by machines. This is the case for example for storage and goods retrieval, with an automata responsible for finding a place available for storing goods, and computer orders controlling the automata for the retrieval of spare parts. Humans are just there to pick them up, according to a product number given by a terminal.

5.1.3 The abstraction gap

The field study conducted in the context of the apprenticeship in logistics allowed us to identify a major issue of the apprenticeship of logisticians, which we call the *abstraction gap*. It describes the difficulty apprentices have to understand the concepts presented at school and relate them to their everyday practice. Two main interrelated reasons explain the gap between school and workplace. On one hand, concepts taught at school are presented in a too theoretical way that is difficult to understand for the apprentices. On the other hand, providing apprentices with the possibility to gather practical experience at the workplace by applying these theoretical concepts would facilitate their understanding, but apprentices usually do not get this opportunity at their workplace. The next sections present in more details these two issues.

School issues

The first issue concerns the presentation of logistics concepts to apprentices at school. The problem is that the curriculum presents logistics concepts in a theoretical way that appears to be disconnected from everyday practice for most of the apprentices. Since many of the apprentices who choose the logistics orientation did not perform well during obligatory schooling, they face great difficulties at school. They do not see the relevance of the theory taught at school and quickly loose motivation. There is a strong variety of levels among a typical class and while some apprentices struggle with the theoretical concepts explained by teachers, the others get bored because the rhythm is too slow for them.

The problem clearly appears in the learning material distributed to apprentices. The skills logisticians should have acquired at the end of their apprenticeship are detailed in an official curriculum plan. Each of them is divided in a list of evaluation criteria rated according to Bloom's taxonomy of educational objectives [Bloom et al., 1956], summarized in Table 5.2. The exercises proposed to apprentices are mainly concerned with the first three levels. At knowledge level (C1), apprentices have to learn definitions and specific terms like for example the names of the different areas of a warehouse. Comprehension (C2) and implementation (C3) are mostly addressed through mathematical exercises (e.g. compute the storage surface on a warehouse blueprint or the storage capacity given the number of shelves). Apprentices fail to see the relevance of these exercises for their everyday practice because they mainly train mathematical skills in a rather disembodied way. As a result, weak apprentices do not understand these concepts and loose motivation. The teachers we observed do their best to ground the logistics concepts they teach by taking many examples from their own practical experience, but recognize that their words are not enough to fill the gap between the theory found in the curriculum and the reality.

C1	Knowledge	Exhibit memory of previously-learned materials by recalling facts, terms, basic concepts and answers
C2	Comprehension	Demonstrative understanding of facts and ideas by organizing, comparing, translating, interpreting, giving descriptions, and stating main ideas
C3	Implementation	Using new knowledge. Solve problems to new situations by applying acquired knowledge, facts, techniques and rules in a different way
C4	Analysis	Examine and break information into parts by identifying motives or causes. Make inferences and find evidence to support generalizations
C5	Synthesis	Compile information together in a different way by combining elements in a new pattern or proposing alternative solutions
C6	Evaluation	Present and defend opinions by making judgments about information, validity of ideas or quality of work based on a set of criteria

Table 5.2: The six levels of Bloom's taxonomy of educational objectives.

Workplace issues

The second main reason for the gap is to be found in the way many companies treat their apprentices. Despite a large variety in the type of companies hiring apprentices in logistics, the type of tasks performed by apprentices are relatively similar. During most of our visits we observed that most of the activities assigned to apprentices are fairly basic and limited to moving boxes with a forklift or perform repetitive tasks. Apprentices are usually not involved in higher level managerial duties which are handled either by the management or by more experienced co-workers. While it seems obvious that apprentices are not supposed to be responsible for crucial tasks such as storage management or warehouse organization who have a direct impact on companies' profitability, we expected apprentices to be introduced in a deeper way about these aspects of their work.

This missing link between theory and practice contributes to aggravate the situation at school since apprentices do not benefit from a practical experience that could help them understand the concepts taught at school. The result, as we observed during our interviews with both apprentices and teachers, is an important loss of interest and motivation for school. Interviews showed that there is no transfer from school to the workplace; when asked to explain the logistics organization of their warehouse in a schematic way, apprentices tended to reproduce with great difficulty the theoretical charts presented at school, without adapting them to their company. An apprentice reported that he liked going to school since he could sleep longer in the morning and seat during the whole day. The opinion of workplace supervisors about school is usually not better. They don't recognize school as necessary for the apprentices to improve their work in the company, but as a useful basis for apprentices willing to get higher level diplomas later in their career. According to them, the theory taught at school is often quite different from the reality of the daily practice. As a result, apprentices do not care about understanding crucial aspects of their profession since they are apparently not relevant for their practice.

5.2 Specific research questions

Our approach to overcome the abstraction gap identified in the previous section is to allow apprentices to practice the theoretical concepts taught at school in an authentic setting and support a progressive move towards more complex and abstract concepts. This section describes the different aspects of the solution we propose with the associated research questions.

5.2.1 Question 4: Practice field, situating learning in an authentic context

The Tinker Environment, described in more details in the next chapter, lets apprentices experiment these concepts on an augmented small-scale model of a warehouse. The objective is to create a stronger link between the theory learnt at school and the experience acquired at the workplace. The concrete representation offered by the warehouse model also aims at facilitating the understanding of basic logistics concepts by presenting them in a situated context, easier to grasp than the traditional disembodied teaching given in schools.

This solution is aligned with the remedies proposed by situated learning to the problems faced by traditional schools teaching [Brown et al., 1989]. More precisely, we implement the concepts presented in *practice fields* [Barab and Duffy, 2000] and *authentic learning environments* [Herrington and Oliver, 2000], which propose to create learning situations that:

- are similar with the context in which knowledge will be used;
- feature ill-defined problem-solving activities;
- provide access to expert performance;
- provide multiple roles and perspectives;
- support collaborative construction of knowledge;
- promote reflection and articulation.

Practice fields [Senge et al., 1994, Barab and Duffy, 2000] denote learning environments which follow the design principles advocated by situated learning with the important distinction that practice fields refers to *quasi* real situations, i.e. "Practice fields are separate from the *real* field, but they are contexts in which learners, as opposed to legitimate participants, can practice the kinds of activities that they will encounter outside of schools. Furthermore, every attempt is made to situate these authentic activities within environmental circumstances and surroundings that are present while engaged in these activities outside of schools. However, these contexts are practice fields and, as such, there is a clearly a separation in time, setting, and activity from them and from the life for which the activity is preparation" [Barab and Duffy, 2000]. The idea of intermediate worlds, that combine some affordances of authentic contexts and some requirements of formal education, could provide apprentices with the opportunities to practice the neglected skills we mentioned in a way that is not disconnected from their experience.

Research question 4

Does a warehouse small-scale model help apprentices in logistics to better understand theoretical concepts?

Our hypothesis is that the practice field created by the warehouse small-scale model can overcome the difficulties encountered by apprentices at the beginning of their apprenticeship in two ways. First, it provides a concrete representation which is easier to understand for apprentices who can observe and explore theoretical concepts in a practical way. Second, the application of these concepts to an authentic context allows apprentices to link the theory presented at school to real workplace situations. Since most of them do not have the opportunity to face these situations in their companies, the practice field allows them to play the role of their boss and see the relevance of theory in practice. The tension between tangibles and abstraction, illustrated by the shortcomings of TUIs in the field of education discussed in Section 2.5.2, is addressed by the next question.

5.2.2 Question 5: From concrete towards abstract representations

The concrete representation offered by the warehouse small-scale model is not enough to satisfy the objectives defined in the curriculum of apprentices in logistics. They are indeed supposed to be able to understand more abstract representations such as warehouse blueprints or numerical data and make some predictions based on them. A learning environment for these apprentices should thus not be limited to the concrete view of a warehouse offered by the small-scale model but propose more abstract representations as well. As discussed in Section 2.5, TUIs face some issues in learning contexts and may prevent learners from reflecting on their actions and moving towards more abstract representations.

Research question 5

Does a TaPE support apprentices in the transition from concrete to abstract representations?

The complementarity of IPFs and TUIs, which we explore in this dissertation, might be relevant for learning environments because it offers the opportunity to present information at different levels of representations: task-specific objects give a concrete view of a situation that can be simultaneously represented in a more abstract way on paper. The resulting approach is outlined on Figure 5.2. The concrete representation given by the TUI is progressively replaced by less embodied, more abstract representations given on TinkerSheets, our implementation of IPFs. We propose to facilitate the transitions by the use of Multiple External Representations (MERs): the same information is presented simultaneously at different levels of representation to facilitate the understanding of more abstract ones. MERs have been proposed as a way to facilitate the transition from one level of representation to another [Ainsworth, 2006]. The main assumption is that presenting learners with several instances of the same information at different levels of representations will act as a scaffold allowing them to understand the more abstract representation by observing how it is related to the more concrete one.

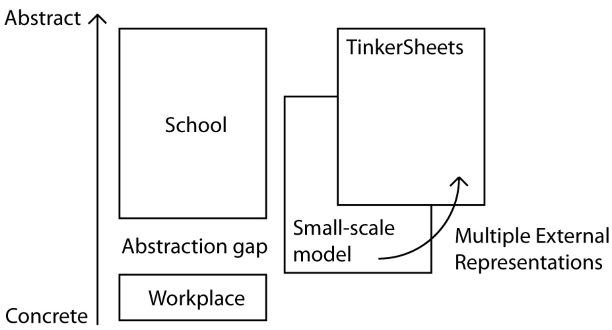


Figure 5.2: The pedagogical approach we propose to bridge the abstraction gap. It takes advantage of the properties of TaPEs to offer a progressive transition from concrete towards abstract representation, facilitated by the use of MERs.

5.2.3 Question 6: Appropriation process

The integration of a TaPE such as the Tinker Environment in a classroom does not come without the question of its appropriation by teachers. A pedagogical intervention usually aims at improving and thus modifying teaching practice, empowering teachers with new tools and approaches. At the same time, a learning environment will not be adopted if it is not adapted to the specific needs of the learning context in which it is integrated and allows teachers to reach the objectives defined by the curriculum. There is thus a tension in the development of a technological learning environment between the pedagogical intentions embedded into its design and the flexibility that has to be offered for the teachers to appropriate it.

Research question 6

What is the appropriation process of a TaPE for teachers?

We have observed during our field study that teaching in logistics training classes was conducted in a relatively traditional way, with the teacher standing in front of the class and explaining theoretical concepts to apprentices. Our aim regarding the introduction of the Tinker Environment in logistics classrooms is not that the role of the teacher would be diminished. On the contrary, we expect that the environment can be used in an effective way only if the teacher takes a central role and guides learners through the activity. The main challenge for teachers may come from the fact that the types of activities organized on a TaPE encourage exploration and discovery by the learners and it is thus impossible for the teachers to know in advance which solutions will be found. Teaching in these conditions thus imply some improvisation and the capacity to take advantage of unexpected events to ensure that learners get to understand the concepts addressed during an activity.

On the other side, the system will not be adopted by teachers if it forces them to strictly adapt to another pedagogical style. It has to offer some flexibility for the teachers to appropriate and integrate it in their daily teaching practice. Flexibility takes place at two levels. First, during the development process, the system has to be adapted to the existing documents and curriculum objectives. Second, the environment should provide some flexibility to the teachers regarding the organization of activities and its actual use in daily teaching. This last point is a trade-off between the pedagogical change the intervention is bringing and the flexibility given to the teacher to adopt it or not. Too much enforcement might probably end up in the rejection of the learning environment while too much freedom may fail to reach the objectives of the intervention.

Chapter 6

The Tinker Environment

THE TINKER ENVIRONMENT is a tabletop learning environment we developed for apprentices in logistics (Figure 6.1). It has been developed over three years with the active participation of two teachers at the Centre Professionel du Nord Vaudois (CPNV) in Yverdon (Switzerland), Jacques Kurzo and André Ryser. The current state of the system is the result of monthly meetings with them as well as continuous observations of its use in classrooms. Figure 6.2 shows an overview of the architecture of the system. The hardware part includes two interactive devices, the TinkerTable and the TinkerLamp, which are Tangible and Paper Environments (TaPEs) composed of a warehouse small-scale model (Tangible User Interface (TUI)) and TinkerSheets, our implementation of Interactive Paper Forms (IPFs). On the software side, the Tinker framework handles task-independent input and output functions used by a logistics simulation. A TinkerTable and four TinkerLamps are currently installed in the classroom of these two teachers while four other lamps are used in a second professional school in Thun (Switzerland). The following sections describe each part of the Tinker environment as it exists now. The reasons that led us to this current design will be reported in Chapter 7.

6.1 TinkerTable and TinkerLamp

6.1.1 Camera/projector systems

The TinkerTable and the TinkerLamp are interactive tabletop environments using computer vision and Augmented Reality (AR) techniques to detect physical objects and project digital information on top of them. This type of device, known as camera/projector systems, capture an image of a scene using a camera, process it using a computer and give real-time feedback using a projector. There are two main families of such systems which differ in the position of the camera and the projector:

Top-projection systems: the camera and the projector are situated above the table surface. These environments have the advantage to be able to project digital information on top of physical objects, but they are sensitive to changing light conditions, occlusions by users' bodies and shadows casted by 3D objects that mask parts of the table surface.

Figure 6.1: A TinkerLamp, the smaller interactive device of the Tinker Environment.

Back-projection systems: the camera and the projector are located below the table, covered by a semi-transparent layer. This approach has been greatly popularized by the advent of cheap and simple hardware solutions based on infrared light like Frustrated Total Internal Reflection (FTIR) [Han, 2005]. This technique can detect both objects and users' fingertips and thus supports a mix of tangible and multitouch interactions. Compared to top-projection, back-projection has the advantage to be less sensitive to light conditions and occlusions by users but can not project information on top of 3D objects and is less comfortable for users since the space below the table is used by the camera and the projector.

Most of the early works on interactive surfaces used top projection. This is the case for example of the Digital Desk [Wellner, 1991], URP [Underkoffler and Ishii, 1999] or the EDC [Arias et al., 1997]. More recent systems almost exclusively use back-projection techniques because of its simplicity and an increased interest in multi-touch and gesture-based interfaces. Some devices are now commercially available, the most notable example being Microsoft Surface [Wilson et al., 2008]. Several approaches have been proposed to get around the limitations of these systems: these include the use of transparent material for physical objects to be able

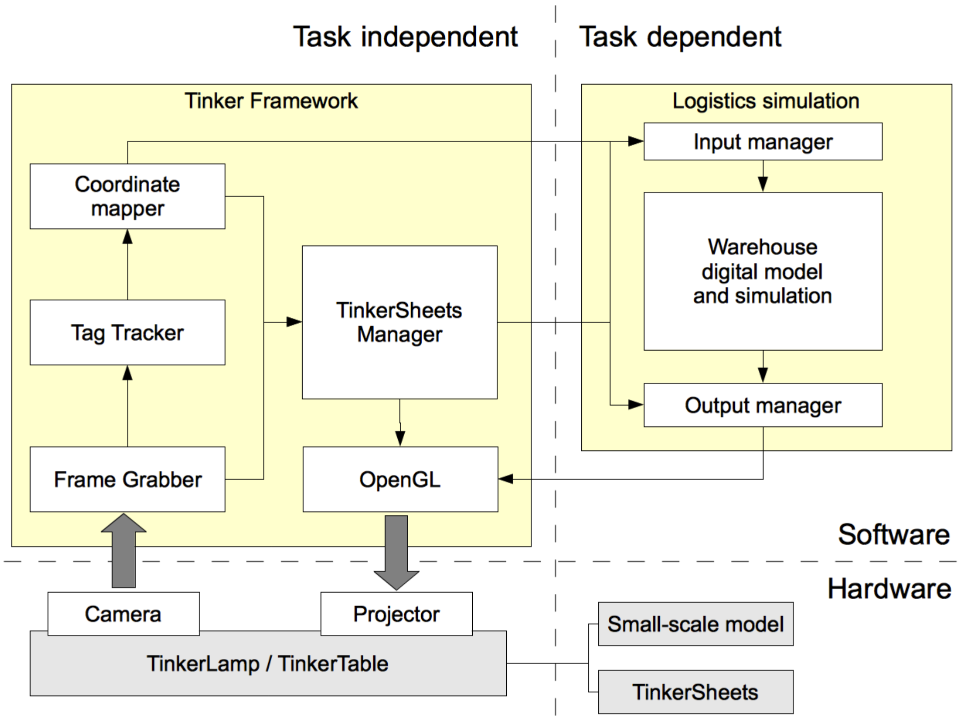


Figure 6.2: Overview of the Tinker Environment architecture.

to display content through them, like for example DataTile [Rekimoto et al., 2001]. A more advanced technological solution uses two high refresh rate projectors and a switchable projection screen which can be made diffuse or clear, allowing the projection of digital information above the table surface [Izadi et al., 2008]. This approach gives access to projections in 3D but is still limited to the back of physical objects or on translucide screens held above the table surface.

Top-projection was chosen for the TinkerTable and the TinkerLamp because it was important in the target application to be able to project information on top of physical objects, in this case the small-scale model of a warehouse. Other systems like URP [Underkoffler and Ishii, 1999], described in Section 2.2.3, would benefit from a back-projection approach since in that case physical objects (buildings) act on their surroundings and the most information is thus on the environment (wind direction, pedestrian flows, . . .) and not on the buildings themselves. In the case of the logistics simulation, shadows casted by shelves on the warehouse floor do not matter since the most important information is to be found on the shelves. This choice turned out to be crucial to support the use of standard paper sheets to control the simulation, which is the case of the TinkerSheets.

Figure 6.3: The TinkerTable.

6.1.2 Hardware description

The TinkerTable consists of a 2.5x1.5m table covered with whiteboard material and a 2.7m high gallows carrying a camera, a projector and a mirror (see Figure 6.3). The camera is located at the top of the gallows and points downwards. The projector, situated at approximately 1.2m from the floor, points at the mirror attached at the top of the gallows. The purpose of this construction is to augment the distance between the projector and the table such that the projection covers the whole table surface. The camera and the projector are connected to a computer which runs the logistics simulation.

The TinkerLamp is a smaller and portable version of the TinkerTable (Figure 6.1). A projector and a camera are mounted in a metal box suspended above a regular table by an aluminum goose neck which is 1.2m high. The size of the interactive surface is approximately an A3 paper (500x375mm). Apart from differences in size and scale, the TinkerTable and the TinkerLamp offer the same functionalities and use the same software.

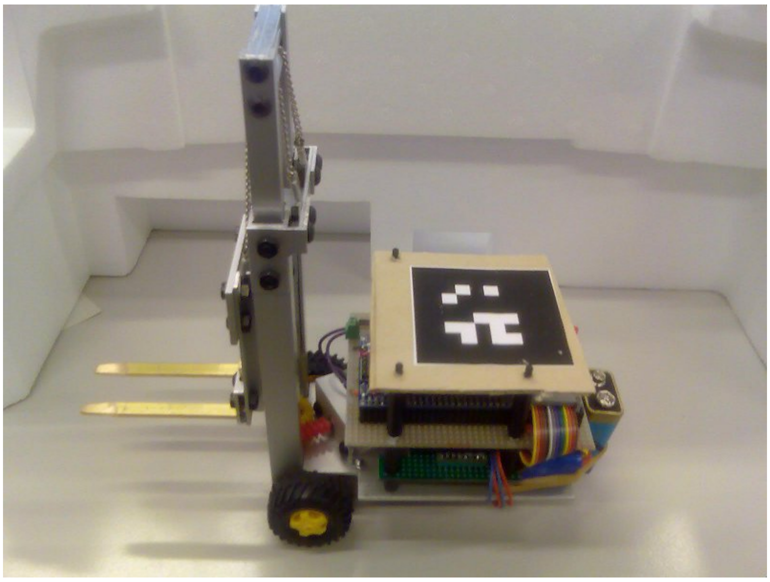


Figure 6.4: Elliot, the remote controlled forklift robot.

6.1.3 Limitations of the TinkerTable

The reason for initially developing the TinkerTable was because we wanted to allow apprentices to work with a small-scale model of a forklift. The objective was to create a small-scale model as close as possible to a real warehouse. We developed a fully functional forklift robot, called Elliot (Figure 6.4). Its two front wheels are independently controlled by two motors and allow it to move and turn. Another motor is used to lift the forks. It can also be remotely controlled with a computer thanks to an embedded radio transceiver. We abandoned further developments of this unique prototype for two reasons. First, it became clear after the first trials with apprentices working with the Tinker Environment that a robotic forklift is not needed. The pedagogical activities that can be organized with a robotic forklift mainly concern navigation issues in a warehouse, which is not a difficult problem for apprentices at school. Indeed, it is the part of the curriculum most closely related with their everyday activities at the workplace. Another limitation of the physical forklift is that it limits the speed of a simulation to real-time. This is again not interesting in a pedagogical context because the pace is too slow to get interesting results in the limited time of a classroom activity.

The TinkerTable was progressively abandoned in favor of TinkerLamps for practical and pedagogical reasons. The practical motivation is that almost 1/3 of a classroom has to be freed to accommodate the TinkerTable. The advantage of the TinkerLamps is that they don't need a reserved space: they can put away when they are not in use and put up whenever necessary. This also makes it possible for several teachers to share a set of TinkerLamps and move them from one classroom to the other. The drawback of the TinkerTable in a pedagogical setting is that it complicates the task of the teacher. Since only 4 to 6 apprentices can work around it at the same time, another task has to be assigned to the rest of the class. As a result, teachers have to monitor several groups working on different tasks in parallel, which proved to be difficult in practice. As we will see in Chapter 7, it is important for teachers to be present and provide a constant guidance for classroom activities to be successful. The TinkerLamps solve this issue because several of them can be placed in a classroom such that enough groups of 2 to 4 apprentices can be formed to get the whole class to work on the same task.

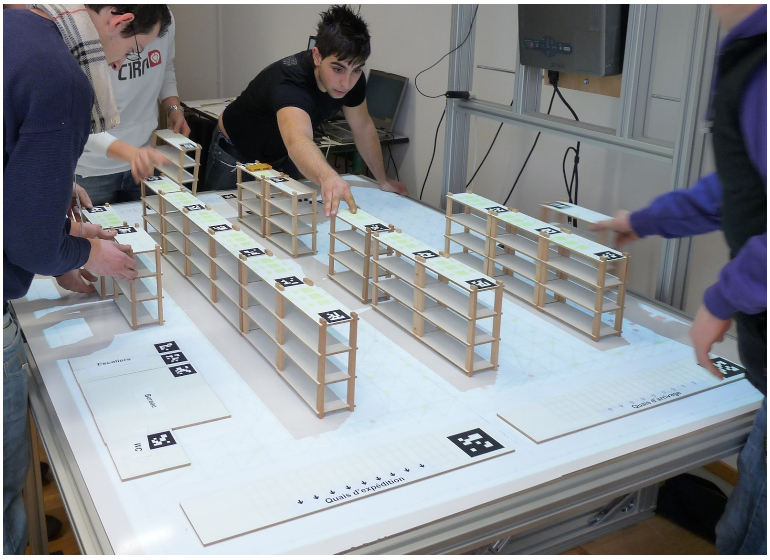


Figure 6.5: A group of apprentices laying out a warehouse on the TinkerTable using shelves, administrative rooms (bottom left), reception and expedition docks (two long wooden plates at the bottom of the image).

6.2 Warehouse small-scale model

The main way of interacting with the TinkerTable and the TinkerLamp is through a small-scale model of a warehouse. On the table, the model is made of wooden shelves (250x60x200mm), delivery and expedition docks (500x120x5mm), metallic pillars (50x50x200mm) as well as a set of wooden plates of different sizes representing administrative areas like offices and technical rooms (Figure 6.5). The same elements are available on the TinkerLamp, but built with different materials and at a smaller scale. Shelves are made of plastic (60x25x55mm), pillars are in wood (20x20x55mm) and cardboard has been used for docks (120x25x2mm) and administrative areas of different sizes (Figure 6.6). The scale is 1:16 on the table and 1:50 on the lamp, which allows the creation of warehouses up to respectively 32x24m and 24x18m. The elements of the small-scale model are recognized by the system thanks to fiducial markers (sort of 2D barcodes) attached to the top of them. These markers will be described in Section 6.4.1.

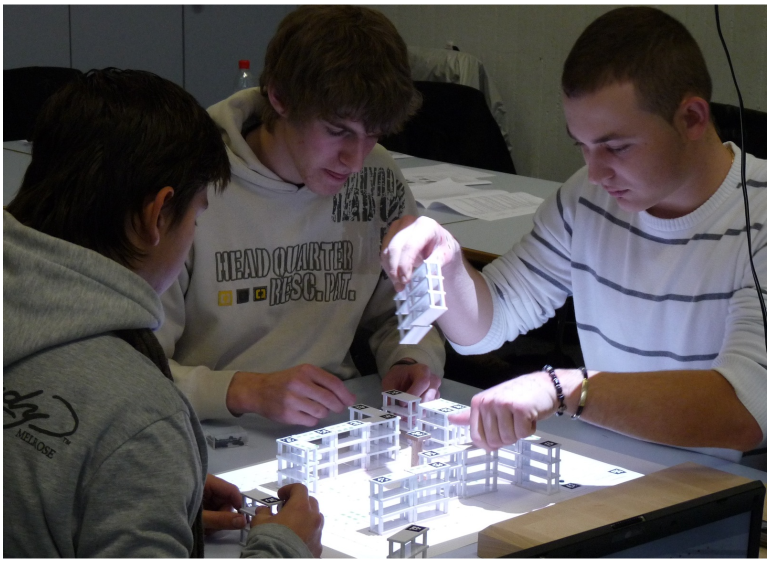


Figure 6.6: A group of apprentices engaged in a warehouse layout task with a TinkerLamp.

6.3 TinkerSheets

TinkerSheets are the IPF interface that we developed for the Tinker Environment. They act as input and output devices that allow users to set parameters and visualize results of the logistics simulation. The concept has been inspired by the work of Johnson et al. who introduced the concept of Paper User Interface [Johnson et al., 1993], already described in Chapter 3. Shortly stated, they proposed to use paper forms to control computer applications: their implementation of the concept took the form of *cover sheets* that were an interface to a document services system, the XAX paper server. Users could simply choose from a number of options on a cover sheet to give instructions to the server, like for example moving the document following the cover sheet to a specific location on the network or output a given number of copies. These documents and their cover sheets were fed to the server through photocopiers or scanners. While cover sheets were targeted to office workers who could edit them on the move using a pen, TinkerSheets are designed for interactive surfaces, provide real-time data through augmentations and use physical tokens instead of pen input. Cover sheets were also limited to asynchronous user input and did not provide feedback. This section gives a description of the TinkerSheets from the user perspective. More details about the implementation are given in Section 6.4.2.

6.3.1 Overview

Figure 6.7 shows an example of a TinkerSheet. It is printed on standard paper and contains both human- and machine-readable content. It uses the same fiducial markers as the elements of the small-scale model described in Section 6.2. While one marker would have been sufficient to identify a sheet, two of them are used to

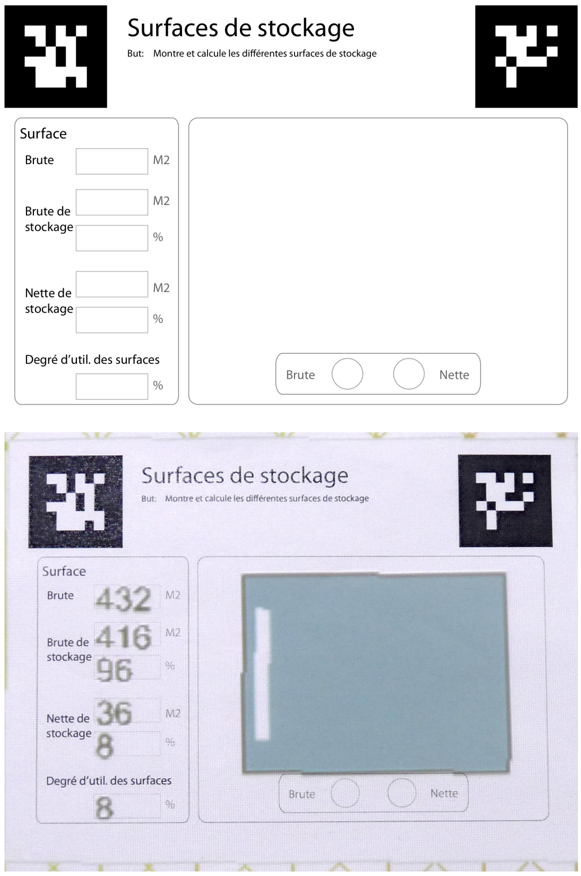


Figure 6.7: A TinkerSheet, including fiducial markers, buttons, feedback zones and textual descriptions. Top: printed content. Bottom: in use, with augmentations.

ensure a greater precision in the estimation of the position and orientation of the sheet on the table. Communication between the users and the system is achieved through a set of basic primitives, like buttons and sliders to control parameters, and feedback zones where text and graphic information is projected. Users interact with a sheet by placing black round tokens on input elements (see Figure 6.8). Since these tokens are visually recognized by analyzing the image captured by the camera, any black round token can be used as input. Magnets with a diameter of approximately 10mm are used on the TinkerTable and small foam pieces with a diameter of 6mm are used on the TinkerLamp. It is also possible to draw a dark circle that respects the dimensions of tokens to fix a parameter. A TinkerSheet also contains printed content addressed to users, such as text and images used to describe the purpose of the sheet.

The bottom part of Figure 6.7 shows a TinkerSheet during its use with the TinkerLamp. The graphic area on the right of the sheet displays a blueprint of the warehouse under construction. The numbers on the left give some quantitative information about surfaces, such as the total surface, the raw storage surface (the part of the warehouse where goods are stored) and the net storage surface (i.e. the area occupied by shelves on the floor, without alleys). This information is updated in real-time: whenever users move a shelf or any other element, the blueprint and the corresponding numbers are updated immediately. Two buttons printed below the graphic area allow users to switch between different visualizations highlighting the numerical information.

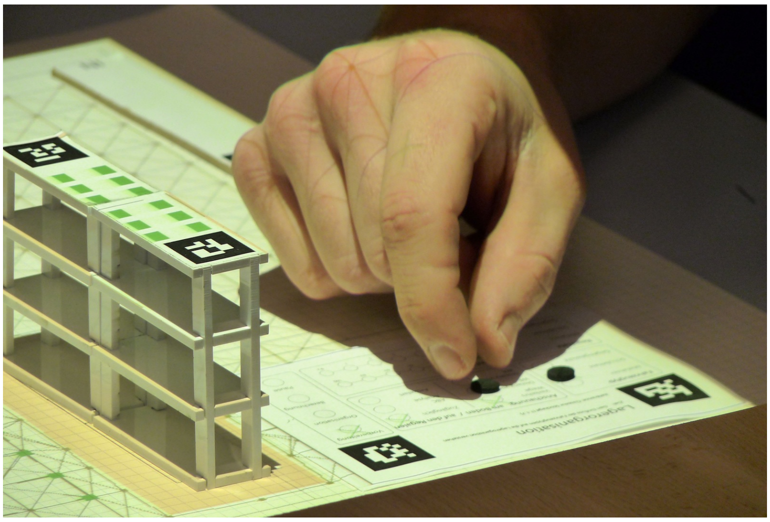


Figure 6.8: An apprentice setting a parameter on a TinkerSheet.

6.3.2 Interaction primitives

This section describes the different primitives currently offered by the TinkerSheets. Input primitives include:

Buttons: usually represented by an empty circle, activated by placing a token on top of them. They are associated with a parameter and a specific value that is set when they are activated. A threshold defines the minimal distance under which a token is considered as being on top of a button (e.g. 3mm for the TinkerLamp). Buttons can be grouped. Groups have the same functionality as radio buttons in a Graphical User Interface (GUI): only one button at a time can be selected. A cross is projected on top of a selected button, green to indicate that the value associated with this button is currently set, red if it is not possible to set this value (Figure 6.9). This usually occurs when more than one token is placed on several buttons of the same group or when the option is not available at that time (e.g. some parameters like the number of forklifts can not be changed when a simulation is running).

Sliders: represented by a vertical or a horizontal line with two short perpendicular lines at its ends, activated by placing a token anywhere on this line. A slider is associated with a range of values, described by a minimum, a maximum and a step size between successive values. Values are spread over the line in a linear fashion. Like the buttons, a green or red cross is projected on top of tokens to indicate whether the value has been set correctly or not. The reasons why a value can not be changed are the same as for buttons.

Tokens areas: these rectangular areas detect the presence and the position of dark round tokens (i.e. the controls used to interact with buttons and sliders). It is used for example during an activity introducing the concept of the gravity center. Tokens can be placed in a box printed on a TinkerSheet, and its gravity center is computed and displayed in real time.

Tag-sensitive areas: these areas detect the presence, position and orientation of specific fiducial markers. This primitive is not heavily used in the logistics simulation. A good example is a toy implementation of the game Pong, distributed over two independent TinkerSheets representing the players' fields. Each player receives a controller used to prevent the ball from touching its goal and send it back to the other player. This controller is only active when placed in the tag-sensitive area of the TinkerSheet.

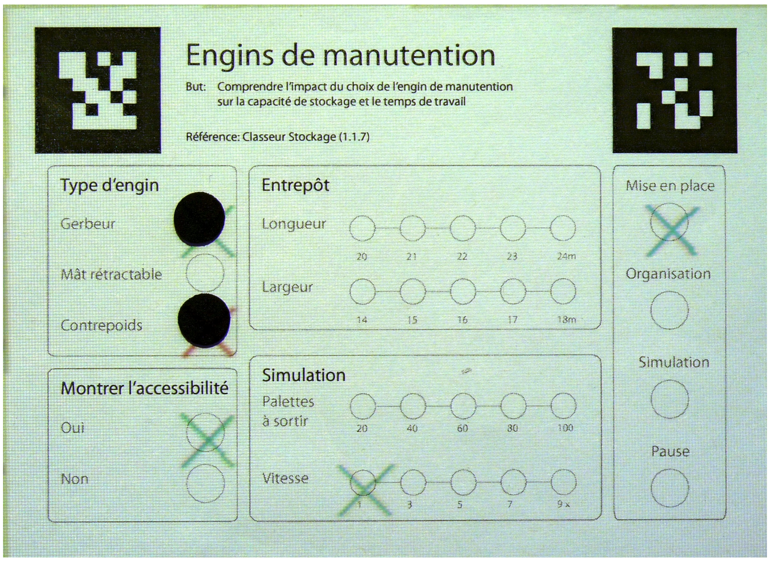


Figure 6.9: Green projected on buttons to indicate the values currently set. Two tokens are placed on a group of radio buttons: a green cross is projected on top of the upper button and indicates that the corresponding value is set; the cross on top of the lower button is red and shows that the value can currently not be modified.

There is currently only one primitive that gives feedbacks to users. It is sufficient to give a large freedom to applications since it only defines a position on a sheet and a size, associated with an identifier. It is then the job of the application developer to generate the necessary graphic output, which can be text, graphics or a combination of them. A possible improvement could be to add more specific primitives taking care for example of formatting and displaying text or offer a customizable chart engine.

6.3.3 Master and companion sheets

TinkerSheets are organized in a two-level hierarchy made of *master* and *companion* sheets. *Master sheets* have the particularity to be associated with an application and a set of default parameters. When a master sheet is detected for the first time, the system loads the corresponding application and sets the parameters defined by the sheet. This mechanism allows putting together different applications developed for the Tinker Environment and switching from one to the other by flipping the pages of a booklet. It also supports the creation of different activities or contexts within an application: each activity is attached to a master sheet which can then be loaded and configured by presenting the sheet to the system. A simple example is a situation where apprentices in logistics have to explore different warehouse layouts depending on the available floor. Master sheets offer a nice way to implement this exercise, by simply providing apprentices with a set of sheets associated with different parameters. The size is printed on each sheet, either through a textual description or by drawing a blueprint of the warehouse. Other interactive elements can also be added like for example a real-time reproduction of the warehouse or statistics about its storage capacity. An important fact about master sheets is that only one of them can be used at the same time since they could set conflicting parameters if used together.

Companion sheets are similar to master sheets except that they do not trigger any event when presented to the system. They simply give access to the elements they contain and can thus be used at any time within a given application. If some sheets may be preferably used with a particular master sheet then external constraints have to be designed to make it obvious for users. These constraints may be as simple as giving a similar title to the sheets and numbers expressing the link between them, but could also be physically enforced with the use of binders to keep related sheets together. This is a nice example of the close relationship between the digital and the real world offered by physical interfaces. Software does not have to control everything but can rely on environmental or contextual constraints to guide users.

6.4 The Tinker Framework

The aim of the Tinker Framework, which was co-developed with Son Do Lenh and Aurélien Lucchi, is to facilitate the development of applications for the Tinker Environment. It acts as an abstraction layer between the application and the system and frees developers from the burden of dealing with low-level processes such as camera frames grabbing, tangible artifacts detection, coordinates mapping from the camera pixel coordinate system to the interactive area coordinate system, TinkerSheets management and rendering. Figure 6.2 shows the main modules as well as their position in a typical application loop. The only input to the framework is the image captured by the camera, captured by the frame grabber and transmitted to the Tag Tracker (described in more details in Section 6.4.1) which role is to detect the position of tangible artifacts and TinkerSheets. These positions are passed to the Coordinate Mapper which converts them from the camera pixel coordinate system to the real-world millimetric coordinate system of the environment's interactive area. The information about the tags detected by the Tag Tracker is then directly transmitted to the application which knows how to interpret them (e.g. tag 42 is a shelf, tag 504 is a dock, . . .). The information regarding the position of TinkerSheets is passed to the Tinkersheets Manager (described in Section 6.4.2) which is responsible for updating the TinkerSheets and send appropriate information to the application. The application receives as input the information about detected tags, commands issued and information to display on TinkerSheets. The output is controlled by the OpenGL settings defined by the framework which ensure that the display is aligned with the interface elements.

Another module that is not represented on Figure 6.2 for the sake of clarity but nonetheless important is the Application Manager. It would be situated between the Tinker Framework and the Application: its role is to route the information sent by the framework to the currently active *application*. The term application is exaggerated since applications in the Tinker Environment are not independent executables but rather independent modules connected to the Tinker Framework through an abstract interface. The application manager does not provide a true multitasking capability to the Tinker Environment: applications that are not in use are put on hold until users come back to them. The objective is two-fold: first, to give the impression to the user that multiple applications are running; second, facilitate the development of additional modules for an existing application. Applications are associated to TinkerSheets and are thus selected by the TinkerSheets manager. From the user perspective, an application is thus simply chosen by showing a TinkerSheet to the system.

Figure 6.10: Examples of fiducial markers. From left to right: Artoolkit, d-touch (original), reacTIVision, d-touch [Costanza and Huang, 2009] and Artag.

6.4.1 Fiducial marker tracking

The system detects the position and orientation of objects thanks to fiducial markers attached to the top of each element of the small-scale model. Fiducial markers are often used in AR systems based on visual detection and recognition of physical objects. They simplify the process by adding features in an image that are easy to recognize using Computer Vision techniques. Marker detection usually takes place in two steps:

Unique feature: detect specific morphological properties of the markers, like a quadrilateral shape with a black border.

Identification: extract a specific pattern from the region where unique features were detected to test whether it corresponds to a valid marker and if it is the case identify it.

Several marker tracking systems have been proposed with different characteristics and limitations. Figure 6.10 shows examples of the fiducial markers used in the approaches we describe below. *Artoolkit* [Kato et al., 1999] uses as a *unique feature* quadrilateral shapes with black borders. The center of the tag can contain any kind of graphical pattern which is used to uniquely identify it. The identification is done by comparing the observed pattern to a set of stored prototypes.

D-touch is based on the topology of markers [Costanza and Robinson, 2003]. A region adjacency graph is created from the structure of the parts of the markers and is used to create an identifier. A marker is made of a black continuous contour which contains a set of four white regions. Each of these regions can in turn contain black areas. The tree is created by recursively extracting white and black regions and the identifier is computed by counting the amount of black regions in each of the four white regions. The unique feature of the markers is that the depth of the tree is limited to three levels, which discards many of the non-marker objects which may compose a scene. A tracking engine based on this principle and optimized using genetic algorithm has been developed for the *reacTIVision* framework [Kaltenbrunner and Bencina, 2007]. More recently, the adjacency trees have been used by [Costanza and Huang, 2009] to create markers readable by both computers and humans.

The Tinker Environment uses another library called *Artag*. It detects markers which unique feature is similar to *Artoolkit*: quadrilateral shapes with a black or white border. Artag is different from the other libraries cited above for two reasons. First of all, the detection of the unique feature of the markers is done using edge detection which is much less sensible to light conditions than thresholding techniques used by most of the other libraries. Second, identification is based on error detection and error correction algorithms that makes it robust to false-positive as well as false-negative detections. The pattern identifying each marker is a 6x6 matrix of black and white squares which create a binary code of length 36. Cyclic Redundancy Check (CRC) as well as a Forward Error Correction (FEC) algorithms are used to encode a set of 2048 identifiers into binary codes. These two techniques are complementary: FEC allows the correction of errors resulting from partial occlusions of markers while the CRC ensures that only valid markers are detected as such, discarding false positives that could be generated by the correction of errors. These properties make of Artag a good choice for top-projection AR systems because it copes well with the tough light conditions and the occlusions by users these systems are facing. It has been compared to an improved version of Artoolkit, called Artoolkit+, and demonstrated superior performance levels both in terms of the detection of markers' unique features and their identification [Fiala, 2005]. The library seems to be unfortunately about to disappear: it is only available for research purposes in a binary version and its development has been stopped.

6.4.2 TinkerSheets Manager

Definition of a TinkerSheet

A TinkerSheet can be seen as a map with the origin set by the top-left fiducial marker and on which interactive elements are placed. The content of a sheet is described in a configuration file which lists the interface elements, maps them to specific positions on the sheet and associates them with parameters and feedbacks of the application. The development framework of the Tinker Environment offers a calibration module that allows programmers to use real-world distances to display content. The size, position, width and height of TinkerSheet elements are then defined in configuration files with their real printed dimensions. This greatly

```
tinkersheet:
{
 radio_buttons =(
   (
    {
     group_id = 0;
     position = [45.0, 84.0];
     name = "forklift_type";
     value = "gerbeur";
    },
    {
     group_id = 0;
     position = [45.0, 93.0];
     name = "forklift_type";
     value = "mat_retractable";
    }
   )
 );

 feedback_zones = (
   {
    id = 0;
    position = [43.0, 31.0];
    size = [45.0, 40.0];
    name = "layout_vizu";
   }
 );
};
```

Table 6.1: An example of a TinkerSheet definition file. This sheet contains a group of radio buttons that let users choose among two types of forklift and feedback zone that displays a blueprint of the warehouse.

simplifies the process of creating a new TinkerSheet. Any image editor or desktop publishing software can be used to arrange the printed content of a sheet, like Adobe Illustrator or Scribus which have the advantage to provide measurements in real coordinates and thus simplify the edition of the associated configuration files. An example of a configuration file is given in Table 6.1. A primitive is defined by the following attributes:

Group id (optional): used for grouping buttons;

Position: x and y coordinates of the primitive; top left corner for areas and sliders, center of the circle for buttons;

Size (optional): width and/or height of the element, used for areas and sliders;

Name: a string corresponding to the parameter or feedback to which the primitive is associated;

Value (optional): a string or a numerical value which is set when this primitive is activated. The situation is different with sliders, for which three values are set (minimal, maximal and step between successive values).

TinkerSheets are centrally handled by a manager class. When the application starts, this manager reads the list of available TinkerSheets from a configuration file. It loads and creates all the necessary TinkerSheets and call at each step the update method of all the detected sheets.

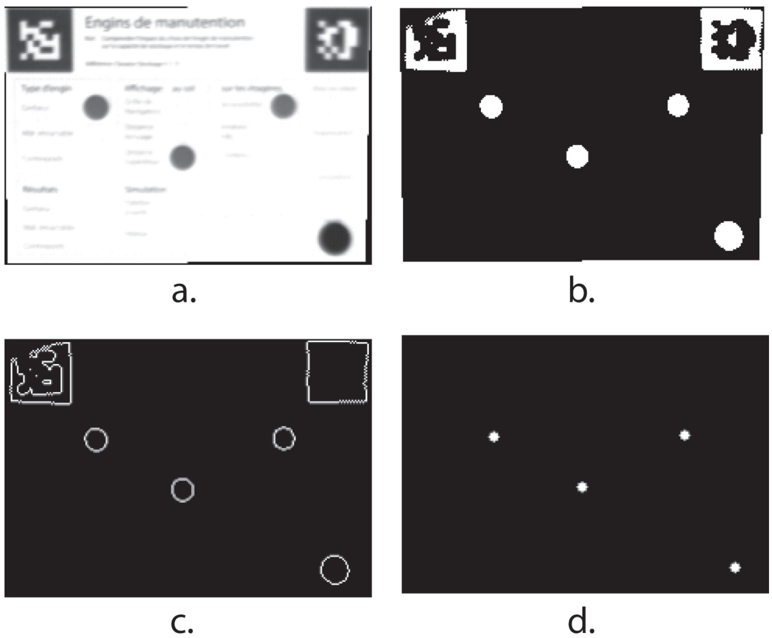


Figure 6.11: The four phases of the algorithm detecting input on a TinkerSheet. a) source image, b) after adaptive thresholding, c) after contour extraction, d) after selection of valid contours: four inputs are detected.

Tokens detection

The algorithm used to detect tokens on TinkerSheets is quite straightforward and has been designed with robustness in mind. This is the reason why, for instance, the shape of the tokens is limited to circles which are easy to detect in an image. Moreover, circles are not likely to appear with typical occlusions by users' hands or objects, which makes their shape quite resistant to false-positives. Another advantage is that circle detection relies on standard functions implemented in OpenCV [1], an efficient open source computer vision library that ensures a minimal processing time. Up to ten TinkerSheets have been used at the same time without noticeable slowing down. The algorithm is made of four steps, illustrated on Figure 6.11. When a TinkerSheet is detected, an adaptive threshold [Bradley and Roth, 2007] is applied on the image to segment dark objects from the background.

[1]http://www.opencv.org

Contours are then extracted and their shape is analyzed. Contours which do not lie within a given size and shape range are discarded. The remaining contours are considered as valid inputs and their distance to each input area of the sheet is computed. If a value below a certain threshold is found the corresponding input area becomes activated and its associated value is set.

Integration into applications

TinkerSheets communicate with applications using a set of specific abstract manager classes. Applications have to implement the managers corresponding to the interaction primitives used on the TinkerSheets associated with them. A pointer to these managers is then passed to the TinkerSheets which will use them to exchange data with the application. The main principle that was followed during the conception and implementation of the TinkerSheets library was to respect a clear separation between sheets and applications. In other words, sheets should not be aware of the meaning of the actions triggered by their interactive elements, and applications should not be aware of the existence of TinkerSheets. The following example, describing the use of buttons, will show how this has been achieved through the use of the abstract managers.

As we have seen in Section (6.4.2), the action of a button is defined by the name of the parameter it controls and the value it should take when the button is activated. The TinkerSheet on which this button is placed does not have to know what this parameter means and how the value has to be modified. Rather, the TinkerSheet calls a method of the corresponding manager class, which was passed as a parameter at the creation time of the sheet, and asks for an identifier corresponding to this name. When the button is activated, the sheet notifies the manager, using this identifier to specify the parameter that is concerned and passes along the value associated with the button. Modifying the value and taking related actions is the responsibility of the application, which knows what the parameter is and can check whether the value is acceptable or not and react accordingly. The application does not explicitly know that the calls come from a TinkerSheet. The managers do not contain any code specific to the implementation of TinkerSheets and could also be used by other types of interfaces like a standard GUI or a touch-sensitive surface.

6.5 TinkerWare: Warehouse simulation

The small-scale model is an interface to configure a digital model of a warehouse which serves as a basis for a logistics simulation. The simulation computes information related to the physical structure of the warehouse such as the distance between shelves, but also provides simple models of customers and suppliers that generate a flow of goods entering and leaving the warehouse. It serves as a basis to illustrate the main concepts addressed during the apprenticeship of logisticians. It is mainly concerned with the designer and manager levels, but also provides extensions for specific concepts of the driver level. It is divided in three main modules implementing the pedagogical approach presented in Chapter 5, moving from concrete towards more abstract representations. Each module is composed of several activities, each made of a set of TinkerSheets (one master and several companion sheets). We now describe in more details each of these modules, following their order of appearance in the apprentices' curriculum. Section 6.5.4 finally gives an overview of the targeted activities developed for the driver level.

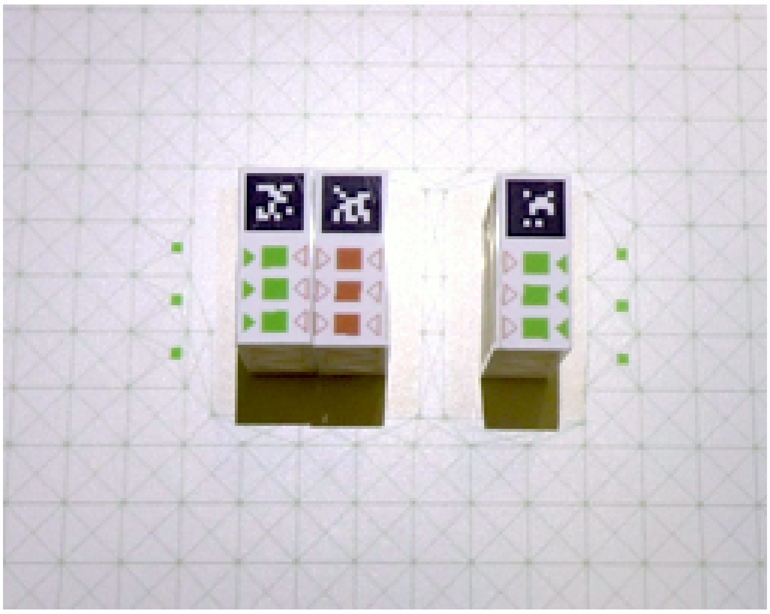


Figure 6.12: The warehouse floor. A regular grid is displayed: it indicates the navigation paths that simulated forklifts can follow. The grid is adapted to surround three shelves; forklifts can still pass between the two shelves on the right because there is a continuous path between them, but the red triangles on the shelves indicate that the alley is not large enough to retrieve pallets from this alley. The middle shelf is not usable for storage, forklifts can not access it from either side.

6.5.1 Module 1: Layout

This module addresses most of the concepts presented at the *designer level* of the curriculum (see Section 5.1.2) and is the basic mode in which the software enters at start-up. The system projects a rectangle which represents the floor of a warehouse. This rectangle contains a regular grid which is used by the simulation as a navigation grid for forklifts. This grid is deformed whenever a shelf is placed in the warehouse to reflect the fact that forklifts can not drive through a shelf but must drive around it. The grid is then useful for apprentices to know whether a forklift can drive through two obstacles, which is possible only if the grid is still visible between them (Figure 6.12).

By default, the system projects information on top of shelves that indicates whether they are accessible or not. Accessibility stands here for the possibility for a forklift to pick and deposit goods in a shelf. A shelf can contain a maximum of 9 pallets on three levels, each divided in three columns. It is accessible if there is enough space for a forklift to reach its content. This information is presented through a square, representing a pallet, surrounded by two triangles pointing towards the

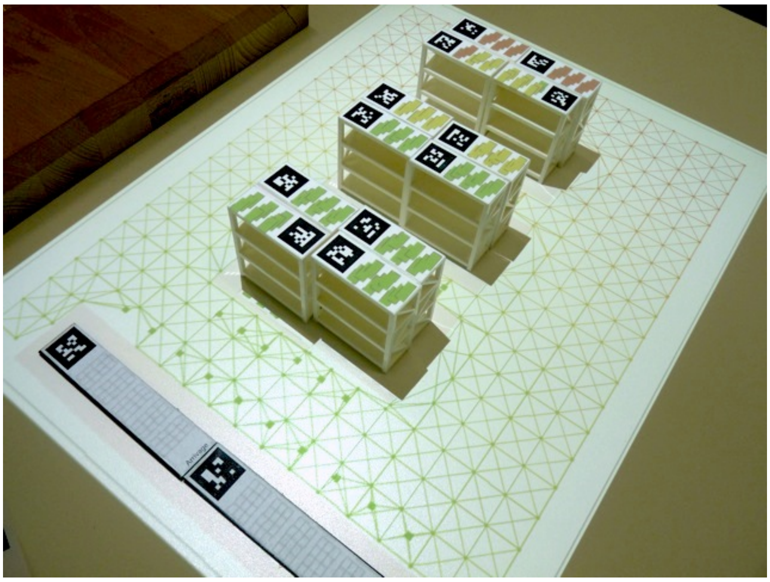


Figure 6.13: Augmentations on a warehouse layout. The top of the shelves shows the result of an ABC analysis: class A products (green) are stored in the closest positions from the expedition dock, followed by class B products (yellow) and finally class C products (red). The color of the grid shows the relative distance from each position in the warehouse to the expedition dock: a green color is used for the closest points and progressively shades to yellow and finally red for the locations furthest apart from the expedition dock.

square. Each triangle is either green or red, indicating whether a forklift can access its content from the corresponding side or not (Figure 6.12). If both triangles are red, the square is red as well. Additional information can be displayed on top of shelves, such as their content or an ABC analysis of the warehouse. The ABC analysis is an application of the Pareto distribution used to organize the products stored in a warehouse in three classes. Class A products, for instance, represent approximately 20% of the stored products but account for 80% of the movements. They are thus placed in shelves close to the expedition dock in order to minimize displacement time (Figure 6.13). Some information can also be added to the floor of the warehouse, such as the relative distance from each point to one of the docks, represented as a heat map going from green for the closest points to red for the furthest away ones (Figure 6.13).

The apprentices can choose among three types of forklifts which differ in terms of size and maximum driving speed. A set of activities gives apprentices the opportunity to experiment with the trade-offs that have to be made in the design of a warehouse layout. Important decisions have to be made regarding the type of forklifts used: it has an influence on the work efficiency (a faster forklift moves more pallets in a given time) and the storage capacity (faster forklifts are bigger, need larger alleys and thus reduce the capacity of the warehouse). These trade-offs are tested by running a simulation that will usually last for the time needed by forklifts

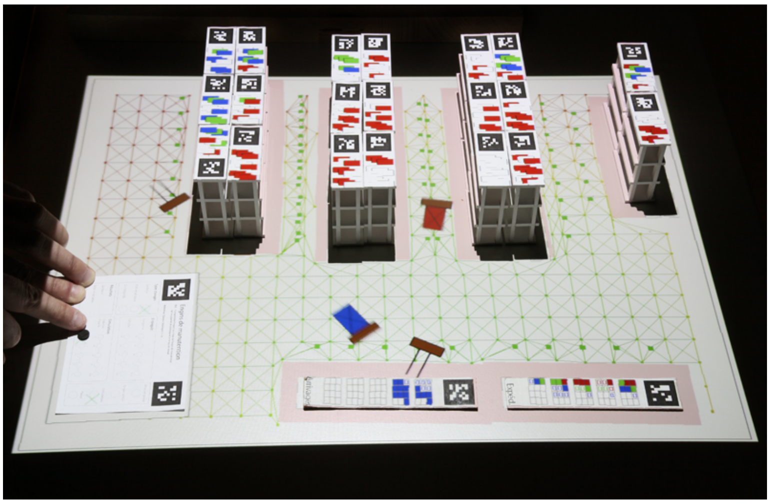


Figure 6.14: A simulation running on top of the warehouse small-scale model. Simulated forklifts move pallets between docks and shelves.

to bring a given amount of pallets to the delivery dock (Figure 6.14). TinkerSheets allow apprentices to follow the evolution of the work, through a set of metrics such as the time elapsed, the amount of pallets delivered and, most importantly, the average time needed by a forklift to deliver a pallet. This last variable varies according to the choices made during the design of the warehouse and is thus very interesting for comparison among groups of apprentices.

In its current form, the simulation does not handle collisions: forklifts simply ignore each other with the only exception that only one forklift is allowed to pick or deposit a pallet at a given position at the same time. Other simplifications have been made to adapt the use of the simulation to a pedagogical setting and make it didactically realistic. The number of product types stored in the warehouse is limited to three. In this first module, only one type of forklift can be used at the same time and customer orders always concern full pallets. Customer demand is adapted to the efficiency of the work performed in the warehouse to ensure a constant flow of goods, and reorders of goods are automatically managed by the simulation: storages breaks and potential over supplies are not part of the objectives of this module. The aim of these simplifications is to limit the variability of factors others than the warehouse layout and the characteristics of a given forklift type, which are the main variables of the activities organized in this module. While collisions are not taken into account, the behavior of each independent forklift is implemented in a realistic way: their size and speed correspond to real vehicles and the simulation takes into account the time needed to lift the forks to reach pallets at different levels of the shelves. Customer demand for each product type is set independently such that apprentices can observe the effect of a warehouse organized according to an ABC analysis of goods compared to a random one.

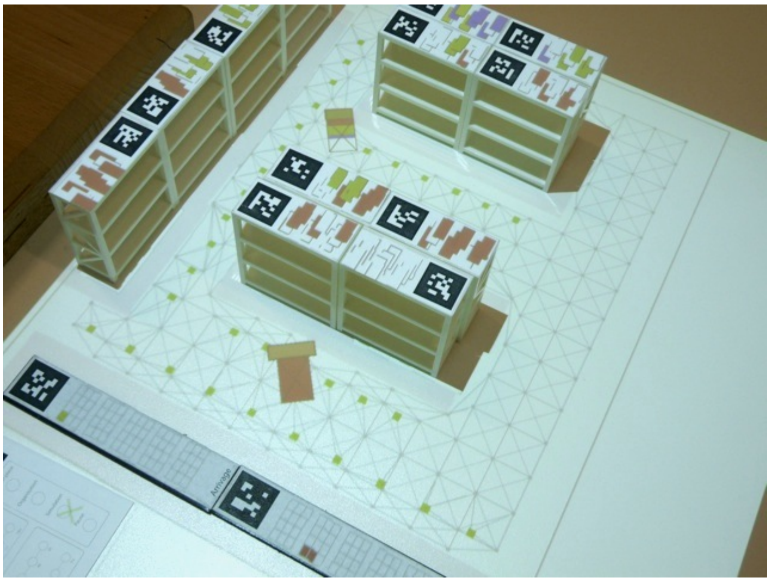


Figure 6.15: Module 2: Two types of forklifts working during a simulation. The larger forklift is responsible for restocking activities: it moves pallets from the delivery dock to the upper levels of shelves, and whenever needed moves pallets down to the floor level. The smaller forklift is a picking forklift: it takes goods from the bottom level of shelves to prepare customer orders. As we can see on the picture, picking forklifts fill pallets with different types of products.

6.5.2 Module 2: Picking

This module takes place at the end of the *designer level* and makes the transition towards the *manager level* (see Section 5.1.2). It addresses concepts related to the organization of work in a warehouse. The initial application setting presented to apprentices is very similar to the previous module. Activities usually start by laying out a warehouse, but the simulation introduces some novelties. A second type of forklift is available, used in warehouses by employees responsible for the customer order preparations (picking). Unlike the layout module where simulated forklifts only handled full pallets, the simulation now allows customers to order fractions of a pallet for each product type.

Activities implemented in this module address the concepts related to the time spent on different tasks by logisticians. These tasks include displacements, organization, picking, dead and lost time. TinkerSheets allow apprentices to change the organization of the warehouse and let them observe its impact on the time spent on each of these tasks. Available parameters include the type of products stored (relatively large, easy to pick items versus small items which take more time), time allowed for pauses which influences the amount of time lost during a day and the type of forklift used (faster forklifts reduce displacement time). Simulations are used to observe the implication on the efficiency through several visualizations. A visualization represents a pie chart showing the percentage of time spent for each

Figure 6.16: Module 3: The simulation adapted for storage management activities. The small-scale model is not used anymore and the warehouse is displayed four times smaller than usual to leave space for TinkerSheets arranged around it. These TinkerSheets allow apprentices to observe the storage level and potential storage breaks for a given product (charts) and control parameters such as reorder threshold and amount, suppliers' delivery time or average customer demand (two TinkerSheets on the right).

activity.

The simulation runs on the same model as in the layout module and ensures a steady level of customer orders. It differs in the sense that it involves two types of forklifts. Picking forklifts prepare customer orders: they retrieve products in the lowest level of shelves, compose new pallets made of different products and bring them to the expedition dock. Restocking forklifts replace empty pallets on the ground with full ones from the upper levels of shelves and bring pallets from the delivery dock to the storage area (Figure 6.15).

On traditional forklifts, drivers are seated and usually do most of their work with their forklift. During picking, employees have to move from one shelf to the other and take items by hand. Picking forklifts are thus usually operated by a person walking next to them or standing at their back. The advantage is that workers can easily leave the forklift to pick items in a shelf. The drawback is that only pallets stored directly on the floor can be accessed by picking vehicles. The warehouse is thus organized so that each product is available for picking at the lowest level of shelves while the upper levels serve as a resupply stock.

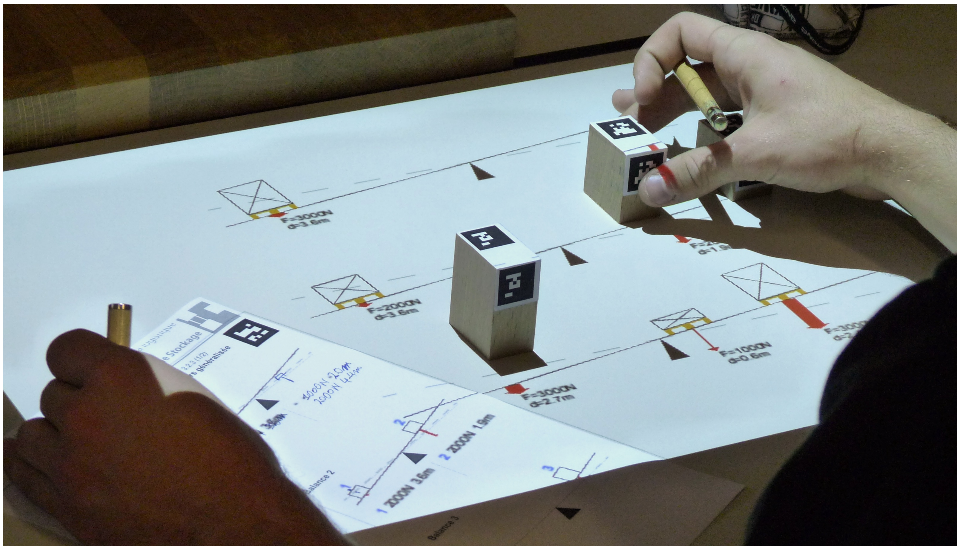


Figure 6.17: Levers law activity: apprentices arrange pallets represented by wooden blocks on projected levers and try to find the equilibrium. The resulting forces are displayed below the boxes and reported on a TinkerSheet.

6.5.3 Module 3: Storage management

This module introduces the most complex notions of the apprenticeship of logisticians. It corresponds to the *manager level* (see Section 5.1.2) and allows apprentices to play the role of the person responsible for the daily management of a warehouse. It focuses in particular on the decisions that have to be taken to avoid storage breaks while keeping the level low enough to limit the storage costs.

The type of representation used by this module is more abstract than in the two previous ones. The small-scale model is replaced by a 2D virtual projection of the warehouse layout, four times smaller than the small-scale model. The goal of this smaller display is to leave more space for TinkerSheets, which are the main interaction modality in this module. It illustrates the shift of focus from the warehouse layout, which is central in modules 1 and 2, to storage management activities where the actual design of the storage looses importance compared to numerical data such as storage level and customer demand.

TinkerSheets allow apprentices to save layouts created previously to reuse them in this module. The simulation also differs greatly from the other modules. It does not show the displacement of forklifts because it runs much faster: one simulated day lasts only two seconds. This is necessary to represent a realistic storage level curve and a correct-time frame of several days between reorders and deliveries. A simulation running at a near real-time would be too slow to observe these events. TinkerSheets display the storage level and potential storage breaks of the different types of products stored in the warehouse (Figure 6.16). Apprentices use a TinkerSheet to set parameters such as the average demand of customers and the delivery delay of suppliers. They use other sheets to manage the storage levels. They can set the limit at which new pallets have to be ordered from the suppliers and also decide on the amount. These parameters can be set according to the Andler equation, described in Section 5.1.2, and allows apprentices to test its validity but also discover its limitations.

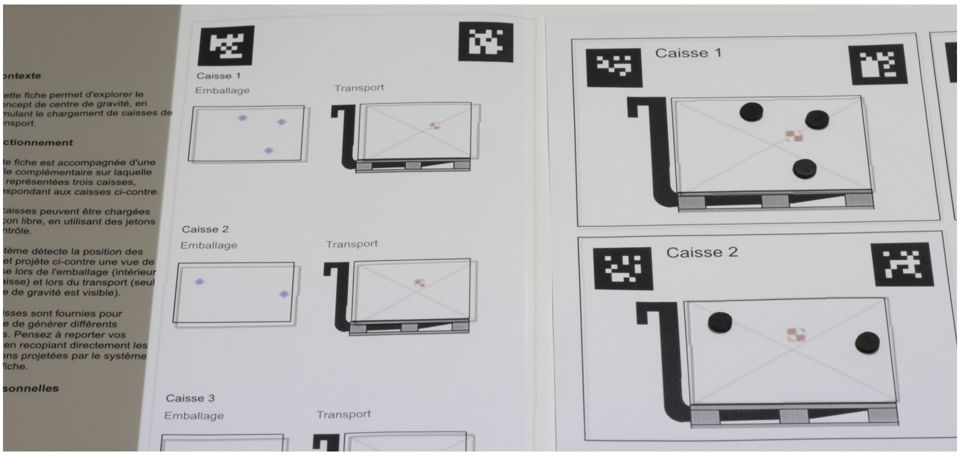


Figure 6.18: Gravity center activity: tokens placed in a printed box (sheet on the right) represent the position of goods and are used to compute the corresponding gravity center, displayed directly on the box and on a second sheet used to write down results (left).

6.5.4 Targeted activities: Levers and gravity center

Beside the warehouse simulation which constitutes the main software component of the Tinker environment, we developed two specific modules that illustrate important physical and mathematical concepts addressed at the *driver level* of the curriculum (see Section 5.1.2). These modules cover the gravity center and the levers law, related to the transport of pallets with forklifts. It is important for logisticians to understand these concepts since they are related with their safety at the workplace.

The *center of gravity module* lets apprentices explore the gravity center concept by arranging tokens in a pallet, printed on a TinkerSheet. These tokens represent the distribution of the mass in the pallet, and the resulting center of gravity is projected by the system (Figure 6.18). The goal is to get apprentices to reflect about the importance of the location of the gravity center of a pallet when moving it with a forklift. A center of gravity placed far away from the forklift may unbalance the vehicle and hurt the driver.

The *levers law module* provides apprentices with a set of wooden tokens which represent pallets of different sizes and weights. They can be arranged on simulated levers which will move according to the distribution of the weights (Figure 6.17). The objective is to allow apprentices to discover the law in an intuitive way. They are asked to create different examples of an equilibrated lever and discover the law by generalizing from these examples.

Chapter 7

Studies

DURING THE THREE YEARS of its development in close collaboration with logistics teachers, the Tinker Environment has been used on a regular basis by those teachers and their apprentices. In line with the Design-based Research (DBR) approach outlined in Section 4.3, we observed the use of the system in authentic classroom contexts on a continuous basis and used these observations to drive the next developments. This chapter provides a chronological account of the evolution of the Tinker Environment through a description of these observations, organized in what we call DBR studies. A DBR study gathers together a set of observations that allowed us to identify and document a particular issue which led to a new design cycle. These observations are usually conducted over a limited period of time with a relatively stable version of the system.

As stated in Section 4.3, we did not limit ourselves to a single research method. The studies reported in this chapter also include controlled and semi-controlled experiments. Controlled experiments are conducted in a laboratory setting; their objective is to test a specific variables identified during DBR studies. Semi-controlled experiments aim to quantify learning outcomes in an authentic context with pre- and post-tests; they were used to compare the Tinker Environment to the traditional pencil-and-paper approach.

The studies are organized in four development phases of the Tinker Environment. Phase 1 corresponds to the early classroom trials that assessed the potential of the warehouse small-scale model to engage apprentices in problem-solving tasks. Two controlled experiments completed these early observations, evaluating the specific affordances of a Tangible User Interface (TUI) compared to a multitouch interface. Phase 2 reports observations that cover the different solutions implemented to overcome the scalability issue of the TUI until the introduction of TinkerSheets. Phase 3 includes three DBR studies that illustrate the use of Multiple External Representations (MERs) to move from concrete to abstract representations at different stages of the apprenticeship. Phase 4 is concerned with observations that describe the development of pedagogical scenarios and show how the TinkerSheets supported the integration of the Tinker Environment in the classroom ecosystem.

The studies took place in three professional schools in the area of the Ecole Polytechnique Fédérale de Lausanne (EPFL), in Yverdon, Thun and Bulle (see Figure 7.1). An overview of the studies and their link with the research questions is given in Table 7.1.

Figure 7.1: The locations where the studies were conducted: Ecole Polytechnique Fédérale de Lausanne (1) and the professional schools of Yverdon (2), Bulle (3) and Thun (4).

7.1 Phase 1: Validating the tangible approach

Three studies aimed at evaluating the potential of our augmented small-scale model approach to support apprentices' understanding of logistics concepts. The first one is a DBR study that gathers observations conducted in classrooms and compares apprentices working on warehouse layout tasks using either traditional pencil and paper tools or an early version of the Tinker Environment. It illustrates how the small-scale model facilitates apprentices' engagement in the task and outlines potential benefits of the tangible approach. The two other studies are controlled experiments that aim at better understanding the specific affordances of TUIs by comparing the use of the warehouse small-scale model to a multitouch interface. This multitouch interface offered the same functionalities as the Tinker Environment and allowed us to assess the effect of tangibility as a unique variable. Study 2 compares these two interaction modalities from a usability perspective, computing individual performance of subjects asked to reproduce a set of warehouse layouts. It shows that the TUI, fostering manipulations of physical artifacts, is in general significantly faster than the multitouch condition where users move virtual objects with their fingers as mice. The objective of study 2 was to serve as a preliminary study to study 3, which addresses a more complex situation by comparing the affordances of the small-scale model with a multitouch interface in a collaborative problem-solving task, similar to the activities observed in Study 1. It confirms the potential of the tangible approach by showing that apprentices perform better and learn more when they use the tangible warehouse small-scale model.

		Questions					
		1	2	3	4	5	6
Phase 1	Study 1				x	x	x
	Study 2	x			x		
	Study 3		x		x		
Phase 2	Study 4	x	x				
	Study 5	x	x	x			
Phase 3	Study 6			x		x	x
	Study 7			x		x	x
	Study 8			x		x	x
Phase 4	Study 9			x		x	x
	Study 10			x		x	x

Table 7.1: Overview of the studies conducted with the Tinker Environment and their link with the research questions.

7.1.1 Study 1: tinkering or sketching

Method

This study encompasses a set of observations conducted in classrooms with apprentices working on a problem-solving task using either traditional pencil and paper tools or the augmented warehouse small-scale model of the TinkerTable. It follows a DBR approach in the sense that observations were made in an authentic context, with teachers giving a normal course to their apprentices. A more detailed report of this study is given by Jermann, Zufferey and Dillenbourg [Jermann et al., 2008].

Material Apprentices working with the small-scale model used an early version of the TinkerTable. The software was rather limited at the time of these observations, but the functionalities used by apprentices were similar to the current version.

Observations The observations of apprentices working with traditional pencil and paper methods took place in a class of a professional school in Bulle which never used the tabletop simulation. We observed a problem-solving activity organized once a year by the teacher. Five groups of three to four apprentices were given the task to design the layout of a warehouse which, given the size of shelves used, satisfies a certain number of constraints such as the number of storage places available, the width of alleys as well as administrative and technical rooms of a certain size. The groups had to draw the 2D blueprint of a warehouse and answer several arithmetic questions such as the amount of workers needed to move a certain number of pallets to the expedition dock during a day (Figure 7.2). The layout also had to be justified with arguments explaining the choices made during the design task. This small report was graded by the teacher. The groups were given four one-hour sessions to perform this task. The teacher was available for questions and advice but the apprentices were free to organize their work. We

Figure 7.2: Study 1: A group of apprentices working on the paper&pencil warehouse layout task.

conducted short interviews with the apprentices while they were working and collected the drawings that they produced.

The use of the TinkerTable was observed on six occasions which differ in terms of the location, the apprentices and the teachers involved and the simulation development state. While five out of these six observations took place in a classroom at the professional school in Yverdon (Centre Professionel du Nord Vaudois (CPNV)), the first was conducted at our university. The reason for this is that it was organized when the TinkerTable was not yet installed in a classroom. The school year was over at that time and two groups of apprentices had to come for an exceptional additional school day. They did it on a voluntary basis, did not get paid but we reimbursed their travel expenses. We tried nonetheless to recreate as much as possible a real context by asking the teachers to give a class as they would do in their school.

All sessions started with the layout of a warehouse by the apprentices. This warehouse was then used as a basis to address further topics in logistics (e.g. optimal placement of goods in the warehouse, optimal picking path for forklifts). We do not consider these later activities in the results reported in this study. The activity was videotaped and the sound recorded with ad-hoc microphones. Groups of four to five apprentices were instructed to design a warehouse layout that maximizes the available storage space. A set of architectural constraints were defined by the teachers through the placement of metallic pillars. Administrative and technical rooms as well as reception and expedition docks also had to be placed. The evaluation criteria was the number of accessible pallets, but the quality and the efficiency of the layout was also discussed by the teachers (e.g. alley width, navigation, average distance between docks and pallets, ...). Unlike the pencil and paper activity described above, this work was not graded.

Results

Although the situations we observed differ in many ways, we can still identify a number of dimensions on which traditional pencil and paper activities differ from the use of a TUI in a warehouse layout task. These dimensions highlight the potential of the tangible approach but also uncover some of their limitations in educational contexts. We now briefly describe each of them through examples gathered during our observations.

Task complexity The pencil and paper condition appeared to be difficult for the apprentices. The constraints given to apprentices can not be directly applied to design decisions but first have to be combined to compute indirect parameters. The minimum storage space defines for instance the amount of shelves needed, which in turn defines the surface of the warehouse after taking into account the width of the alleys and the space needed for administrative and technical rooms. The warehouse can then be segmented into different areas. Arranging a set of rooms given in square meters to a rectangle (reasonable shape for a warehouse) appeared to be difficult for many apprentices. Some groups simply reproduced the organization of their workplace, even if it was not adapted to the situation and did not include the same rooms. We also observed a group who solved the problem by simply linking together squares respecting the dimensions of the rooms (Figure 7.3).

The use of the small-scale model greatly reduces the complexity of the task. Apprentices are given a set of predefined objects, which removes from the problem the difficult choice of the different areas' shape and size. The tangibles simplify the representation of the problem and free the mind of apprentices to build and explore potential solutions. The problem is neither simple since arranging shelves, docks and administrative rooms in a warehouse still offers an almost infinite solution space, in particular when pillars have to be taken into account. In the paper condition, apprentices have to define both the dimensions of the warehouse components (rooms and storage area) and their position. The TUI makes the problem more tractable for apprentices by fixing the size of the elements.

Evaluation of proportions Respecting the relative proportions of rooms as well as warehouse elements such as shelves and docks appeared to be challenging for most of the groups in the pencil and paper condition. Figure 7.4 gives a clear example of these difficulties. This warehouse layout seems to be well equilibrated at first sight, but strong inconsistencies can be found when looking at the different annotated sizes. Labels A1 and A2 represent the same geometric length on the blueprint but have been given values with a tenfold difference (51m and 6m). The values given to the blueprint width and height are also inconsistent because the longer side B2 is labeled as smaller than the shorter one B1 (22.5m versus 67.5m). The difficulty to interpret proportions from a 2D blueprint has been confirmed by the teacher who confessed that obvious weaknesses of layouts are often not detected by apprentices who do not seem to be able to relate a blueprint to a real

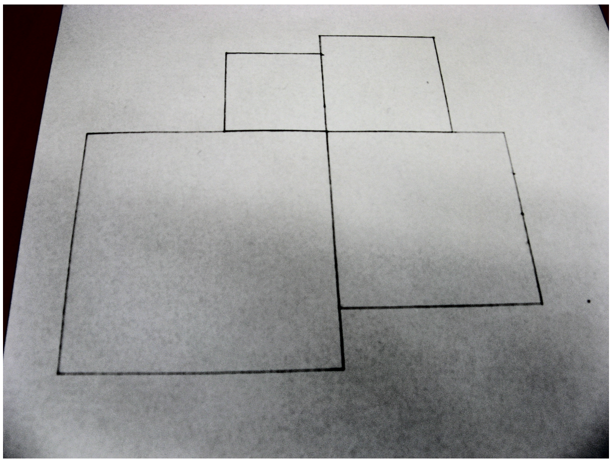


Figure 7.3: Study 1: A warehouse layout that respects surface constraints but that does not correspond to a warehouse typical rectangular shape.

warehouse. This is indeed a difficult task since it implies to be able to recreate a 3D model from the 2D drawing and imagine forklifts moving pallets through the warehouse.

Proportions appeared to be easier to grasp for apprentices in the tangible condition. Apprentices were usually able to roughly estimate the distance that they should leave between two shelves such that a forklift could access their content. Different types of help were nonetheless given by the TinkerTable. In one session apprentices used Elliot, our forklift small-scale robot (see Section 6 for a description), to estimate this distance. In another activity, pallets were added together to compute lengths (a pallet has a standard size of 1.2x0.8m). The software development taking place on the TinkerTable then made it possible to compute shelves' accessibility and display it through augmentations.

Comments made by apprentices during the activity also illustrated their capacity to link the small-scale model to a warehouse and detect potential problems. On one occasion, for instance, an apprentice commented on the placement of a shelf by a group member by saying: "it doesn't work like that, if there are several forklifts working together, it won't be wide enough!". This shows that the apprentice was representing himself the situation and felt that the shelf as placed by his colleague would be a problem. It is also interesting to note that they were not instructed during that session to consider navigation and work efficiency. This apprentice reacted as a logistician, considering the small-scale model as an authentic warehouse and thus caring about designing it based on practical rather than theoretical criteria.

Exploration of the solution space The warehouse layout task is an example of an ill-defined problem: there are multiple solutions, they can not be found through established procedures and there is no unique evaluation criteria. Designers address this type of problems through sketches: they first draw a quick outline of a

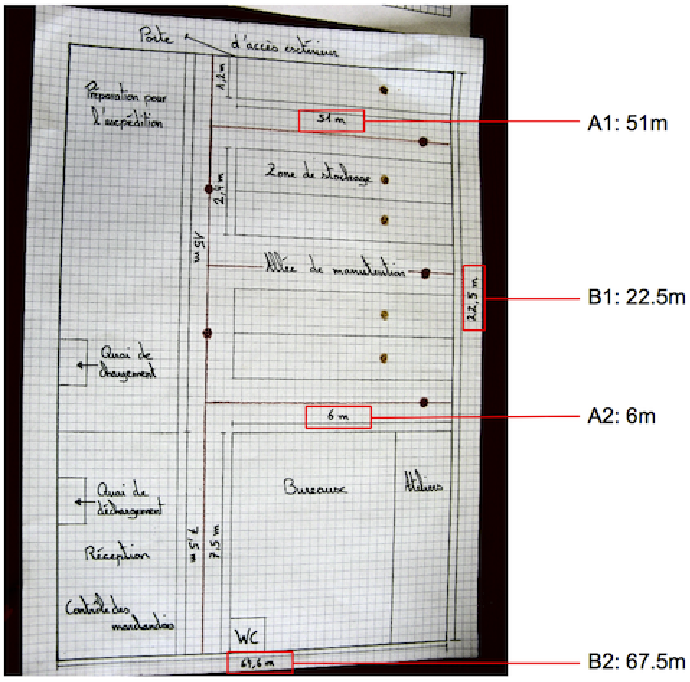


Figure 7.4: Study 1: An example of the difficulties apprentices regarding the evaluation of proportions. Labels A1 and A2 represent the same geometric length, but were assigned very different values (51m and 6m). Labels B1 and B2 represent respectively the longer and the shorter borders of the warehouse, but B1 is smaller than B2 (22.5m and 67.5m).

potential solution, using fuzziness to indicate that the solution is not frozen and encourage modifications and refinements. Sketches act as external representations of ideas or concepts: they free mental resources by becoming separate objects that can be easily manipulated and modified [Buxton, 2007]. Sketching would thus be a powerful strategy in the warehouse layout task since it would let apprentices start with a rough initial arrangement of rooms and progressively refine it until reaching an acceptable solution. It was unfortunately not the case (Figure 7.5). The groups we observed tended to draw only one or two solutions, without sketching, probably because their attention was absorbed by other drawing constraints such as the scale. Apprentices spent a lot of time thinking about the problem, often appearing stuck, before drawing very carefully, at once, a complete solution. Rather than using drawings as a way to build the solution, the emphasis was put on communicating it with a focus on precision.

We observed a different pattern in the tangible condition. Groups usually started the implementation of the warehouse immediately or after a very short discussion. Compared to the pencil-and-paper situation where apprentices spent a lot of time thinking before producing a solution, the tangible condition put an emphasis on trial and error. The design did not follow a global planning but rather grew incrementally: once an apprentice had placed the first shelves, the others simply added new ones based on them, considering local constraints only. The tangible modality supported a higher degree of exploration, although limited to a local context. Before placing a shelf, apprentices would usually position it at several locations in different orientations to find the best solution. The warehouse was thus progressively filled with shelves up to the point where no more space was available. Groups were usually satisfied at this point and did not propose by themselves to try out a different layout. This usually had to be triggered by a discussion with the teacher.

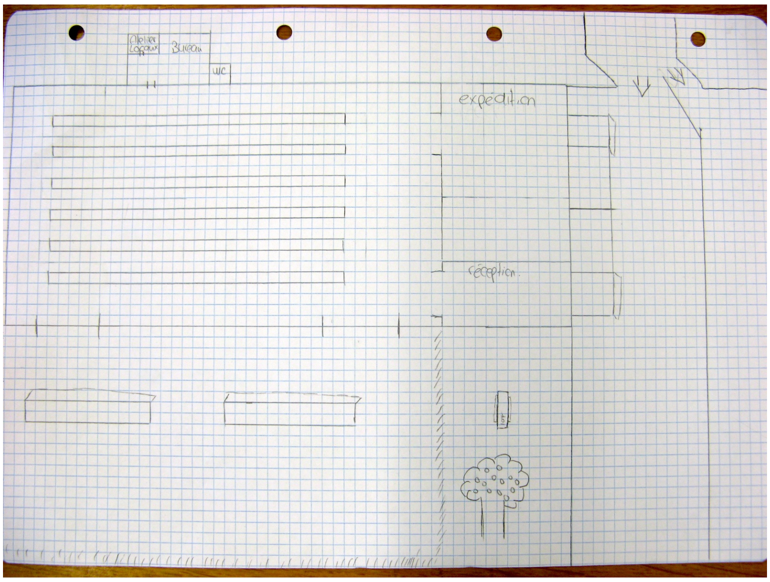


Figure 7.5: Study 1: Another example of a layout designed during the paper&pencil activity. Apprentices did not sketch but rather directly produced a final solution.

Activity duration The time needed to complete the task was strongly dependent on the type of tools used: groups working on the pencil-and-paper problem did it during 4 hours, including initial computations, warehouse layout and answers to arithmetic questions; groups in the tangible condition designed a warehouse in about 10 to 15 minutes. These two values are of course not comparable since the pencil-and-paper task was more complex and demanded more work, but it is still worth considering how the time is used. Over the four hours dedicated to the pencil-and-paper exercise, apprentices appeared to spend much time being stuck, not knowing how to handle the problem and where to start from to build a solution Comments such as "*we are not architects*", "*how could we know how to do this?*" were often heard during this step. Long minutes were then spent drawing the solution, a task done by only one apprentice in each group. The teachers also reported that the solutions produced by the apprentices were usually not very good, with important flaws going unnoticed and exacerbated by the difficulty they have to evaluate proportions.

While the solutions produced in the tangible condition were usually not better, the short time needed for creating them gave the opportunity to the teacher to give feedback to the groups, discuss their solution, ask them to criticize it and encourage them to try it again after defining a strategy. In the four hours needed for the pencil-and-paper exercise, the same group of apprentices can thus do several iterations of a warehouse layout task and still solve arithmetic problems. More time can be dedicated to feedback and discussion.

7.1.2 Study 2: usability study - comparison of individual performance using a Tangible or a Multitouch interface

The first study demonstrated the potential of a TUI to support apprentices during problem solving tasks compared to pencil and paper exercises. Because of the large number of variables inherent to field studies, it was difficult to get a clear answer regarding the role played by the physical model during these sessions. This is the reason why more controlled experiments were conducted, with the aim to better understand the importance of physicality for apprentices during collaborative problem-solving tasks. This second study was designed as a preliminary usability study, preparing the ground for Study 3. It compared the individual performance of participants in a warehouse layout task using either a tangible or a multitouch interface. The study aimed to assess the impact of TUIs affordances on speed and error rates compared to the multitouch interface. The main hypothesis was that participants in the tangible condition would be faster than in the multitouch condition. The work reported in this study was mainly conducted by Aurélien Lucchi. A more detailed account of the results presented here is given by Lucchi, Jermann, Zufferey and Dillenbourg [Lucchi et al., 2010].

The reason why a multitouch interface was used is that it provides the same setting as the tangible condition, with a unique exception: participants manipulate virtual shelves instead of physical artifacts. The comparison of tangible and multitouch interfaces thus tests only one variable, tangibility. More variables would change with a Graphical User Interface (GUI) interface for instance, such as the orientation of the display (vertical vs horizontal), the type of input (direct vs mediated by a mouse) and the amount of parallel inputs (single user vs multiple users).

Method

Participants The participants were 40 students (14 females and 26 males) from the university campus, aged between 14 and 30 years and with differing backgrounds (technical and non-technical). They received 20 Swiss Francs for their participation to the experiment. Out of the 40 participants, 15 owned a touch-screen device and 32 had used a multitouch interface before the experiment.

Procedure The study took place in a closed experiment room in the presence of the experimenter. The introductory part for the multitouch condition included a four-minutes long movie explaining the different actions available, such as adding an object, lasso selection or scaling. The goal of this movie was to ensure that each participant was aware of the possibilities offered by the multitouch interface. This was not necessary in the tangible condition since all the available actions involved

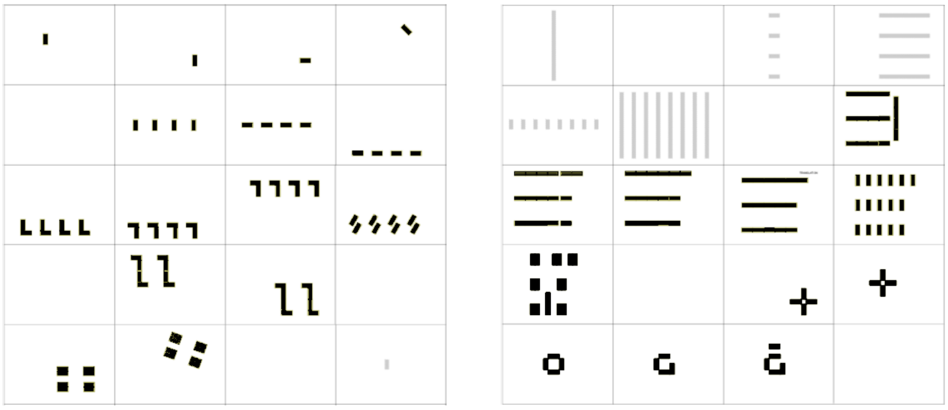


Figure 7.6: Study 2: Layouts that had to be implemented by the participants. Brown (dark) and grey (light) colors represent shelves and walls, respectively.

physical manipulations of tangible artifacts which are known from everyday experience and thus did not have to be explained.

Participants then went through a familiarization session (two minutes) and started the experiment with an empty warehouse. They were asked to implement 40 layouts, shown on Figure 7.6, in a fixed order. These layouts had to be implemented twice by each participant: once with the tangible interface and once with the multitouch interface. For each layout, participants had to place shelves and walls accordingly, submit it by touching a specific button and continue with the next layout by moving objects from the last one and adding/removing some whenever necessary. The experimenter told them to complete the task as quickly and accurately as possible, but no time limit was given. The experiment was video-taped and log files recorded each action performed by the participants as well as the completion time of each layout. The number of necessary moves from one layout to the next one was limited to either 1, 4, 8, or 16 moves to facilitate the comparison of the time needed to produce each layout. The layouts were designed to include only translations, rotations or both.

Material The setup consisted of a TinkerLamp placed on a custom multitouch table (107x107cm), as shown on Figure 7.7. The multitouch table was used only an input mechanism to detect users' fingers and relied on the projector of the TinkerLamp to display information. The software used for both conditions offered exactly the same functionalities and thus only differed in the type of interface used to create the warehouse. Figure 7.8 shows a screenshot of the interface in the multitouch condition. Virtual buttons at the top of the interactive surface allowed users to add objects to the warehouse (shelves and/or walls), undo actions, perform selections and submit a layout. In the tangible condition, the multitouch table was switched off and apprentices used the small-scale model with the TinkerLamp to build a warehouse. In the touch condition, the apprentices used drag-and-drop gestures to create, move and delete shelves and docks.

Figure 7.7: A TinkerLamp placed on the multitouch table used in Studies 2 and 3.

Results

This section reports a selection of the key results obtained during this experiment. We limit ourselves to the analysis of the completion time which is the most relevant aspect in the context of this dissertation. A more detailed description is given in [Lucchi et al., 2010], including an analysis of the accuracy in each condition and a deeper discussion of the implications of this study for the design of tangible and multitouch interfaces.

Results show that order (tangible or mutitouch condition first) did not significantly impact performances and is thus ignored in the following analysis. Table 7.2 shows the average, median, minimal and maximal completion time of the whole experiment for each condition. Participants were significantly faster in the tangible condition than with the multitouch interface (t=-12.51, p<.001). The greater variance in the completion time for the multitouch condition (F[1181,1181]=5.45, p<.001) shows that some participants were nonetheless efficient with this interaction modality and might be explained by the greater familiarity of some participants with

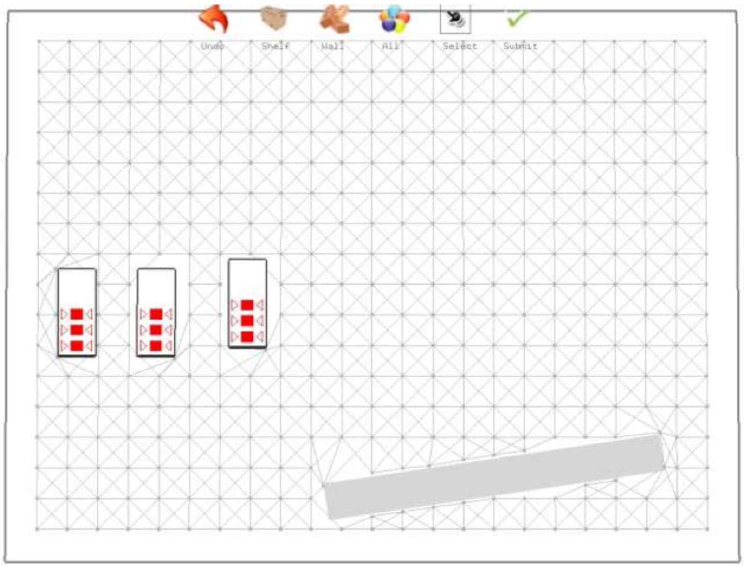


Figure 7.8: Screenshot of the multitouch interface used in Study 2 and 3.

	Mean	Median	Min.	Max.
Tangible	23.82	24.72	13.41	38.34
Touch	28.74	29.63	18.50	42.97

Table 7.2: Study 2: Completion time (in minutes) for each condition.

these interfaces. This was confirmed by the video recordings who revealed that the fastest participants were at ease with the multitouch interface and made a heavy use of features such as undo and select all buttons.

A finer analysis considering completion time for individual actions revealed a more complex picture with differences varying from one type of action to the other. Participants were faster in the tangible condition for rotations (-1 sec. per action), adding shelves (-4.8 sec. per action) and fine adjustments (-2 sec. per action), but were slightly slower for simple translations (+0.47 sec. per act). One of the hypotheses was that a multitouch interface would be faster than the TUI for grouped actions (e.g. lasso selection) but it was not the case: grasping several shelves could still be done at once with both hands. This is probably valid only in this context since the number of shelves involved is relatively limited. There is a point where moving a high number of small objects at the same time becomes faster with a multitouch interface.

7.1.3 Study 3: comparison of a collaborative problem-solving task with a Tangible or a Multitouch interface

The aim of this study was to assess whether the differences in terms of usability between the tangible and the multitouch interfaces observed in Study 2 have an impact on apprentice's collaborative problem-solving activities. More specifically, it sought to evaluate whether the physicality of TUIs is associated with learning benefits, performance increase and collaboration quality improvements.

The main hypothesis was that the tangible condition would lead learners to explore more alternatives and achieve better warehouse designs than with the multitouch interface. More exploration could also have a positive impact on the understanding of higher level warehouse layout rules, thanks to the exposition to a larger amount of examples. The concrete representation offered by the small-scale model may also allow apprentices to apply intuitive knowledge from their workplace experience to evaluate their solutions and facilitate the discovery of general principles.

Two additional process variables were considered in this study: the quality of collaboration and the perceived playfulness of the interface. The hypothesis was that the tangible interaction modality may lead to a better coordination among apprentices and offer more fluid interactions. Moving an object in the multitouch condition can be cumbersome because fingers have to continuously touch the table surface and may thus have a negative impact on a collaborative setting (Figure 7.9). The expectation regarding the perceived playfulness was that it would be higher among participants in the tangible condition. This is a quality often cited in the field of TUIs and the results of Study 2 may indicate that participants would have more fun in the tangible condition because of its higher efficiency which allows them work faster and focus their attention on other aspects of the task.

This experiment has been mainly conducted by Bertrand Schneider. A complete report of this work is given by Schneider, Jermann, Zufferey and Dillenbourg in [Schneider et al., 2010].

Method

Participants The participants were 82 apprentices (9 females and 73 males) from the CPNV, aged between 16 and 40 years (mean=20, SD=5.4). The dyads were composed by alphabetically following the class list and were randomly assigned to either the tangible or the touch condition. 30 apprentices were in their first year (N=16 in the touch condition, 14 in the tangible condition) and 48 were in their second year (N=18 in the touch condition, 30 in the tangible condition). Two dyads were excluded because of technical problems during the experiment. All the participants were familiar with the Tinker Environment since they used it at least once before the experiment.

Procedure The experiment took place during normal school days, in a closed and soundproof room at CPNV (Yverdon). Pairs of apprentices were allowed to leave the class for the duration of the experiment. They were randomly assigned to the tangible or the touch condition when they arrived at the experiment room. After

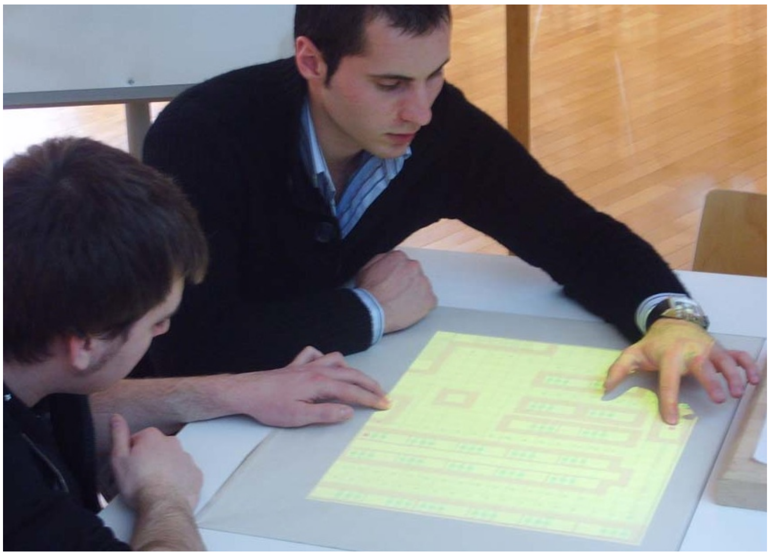


Figure 7.9: Study 3: Two apprentices working on the warehouse layout task in the multitouch condition.

welcoming them and thanking them for their participation, the experimenter asked them to individually complete the pre-test during approximately 5 minutes. 10 minutes were enough for most of the apprentices. They were then asked to solve a problem with the TinkerLamp and received the following instructions: *you have to build a warehouse in order to put the maximum number of shelves possible. This is your primary goal; moreover the efficiency will also be assessed (i.e. the mean distance from each shelf to the reception and expedition docks). You will have approximately 25 minutes to build your warehouse in order to maximize the space used. Try to make most of the shelves accessible and to maximize the space used.* The use of a TinkerSheet to display numerical properties of the layout was also explained. The following information were available on this sheet: number of shelves, number of accessible storage places, average distance to the expedition dock, average distance to the expedition dock and average distance to both docks. To add some complexity to the problem, two pillars and a wall were placed in the warehouse at fixed positions. The dyad then had 25 minutes to design a layout. The experimenter informed them about the remaining time on a regular basis during the last five minutes.

The possible actions were: add, move or remove a shelf, read numerical values from the TinkerSheet and move docks. Two cameras and a microphone were used to record the task. Apprentices then individually filled a post-test, identical to the pre-test except for the warehouse's layout on which the questions were posed. They finally answered a questionnaire which asked them demographical questions (age, sex, apprenticeship year) and a flow questionnaire. There was no time limit for this last step, but the whole experiment did not exceed 60 minutes for any apprentice. They were thanked again for their participation and asked to get back to their classroom.

Material The same setup was used as in Study 2, except for the multitouch interface which was slightly different. It did not allow participants to add, remove and scale walls, and the button used to submit layouts was removed.

Each dyad was recorded with one webcam at the top of the table and one video recorder on the side. An additional microphone (AKG C400 BL) recorded discussions with a better quality than the camera's embedded microphone.

Several questionnaires and observation grids were used: ad-hoc pre-test and post-test were designed to measure learning gain; the collaboration was assessed by an adapted grid of the rating scheme developed by Meier et al. [Meier et al., 2007]; the flow was measured with an adapted questionnaire of Novak et al. [Novak and Hoffman, 1997].

Measures Two criteria were used to evaluate the performance of each dyad: the number of accessible shelves in the warehouse, computed automatically by the software, and the average distance from the expedition and the reception docks to each shelf, obtained by analyzing the logs.

The learning gain was computed by subtracting the post-test score from the pre-test score. These tests were composed of two parts: the first part evaluated the apprentices' capability to judge warehouse layouts by considering the trade-off between use of space and navigation efficiency; the second part asked questions related to general principles of warehouse design such as: *"to gain space, is it better to use short/long/narrow/large alleys?"*. The same questions were asked in both tests, but different warehouse layouts were used for the first part.

Measures also included motivational, behavioral and cognitive process variables. The rating scheme developed by Meier et al. [Meier et al., 2007] was used to assess collaboration quality. Nine dimensions captured the main characteristics of collaboration: communication, joint information processing, coordination, interpersonal relationship and motivation. Each dimension was rated on a five points scale and the sum of these formed the final collaboration score.

The degree of exploration of each dyad was measured by counting the number of times each object was moved (docks and shelves). The values were obtained from the log files and a threshold had to be defined for each condition to filter out micro-movements (e.g. fiducial marker detection is noisy and returns values varying over 1 to 2 pixels).

A flow questionnaire captured the main characteristics of the playfulness variable. Flow has been defined by Csikzentmihalyi [Czikszentmihalyi, 1996] as *the state in which people are so involved in an activity that nothing else seems to matter; the experience itself is so enjoyable that people will do it even at great cost, for the sheer sake of doing it.* For the purpose of this study, the flow was operationalized through an adaptation of the tool developed by Novak et al. [Novak and Hoffman, 1997]. Apprentices were asked to rate items such as "*I forgot about my immediate surroundings when I was building my warehouse*", "*building a warehouse challenges me*" or "*I felt excited during this task*" on a five point Likert scale. These answers were used to evaluate how much they enjoyed the task.

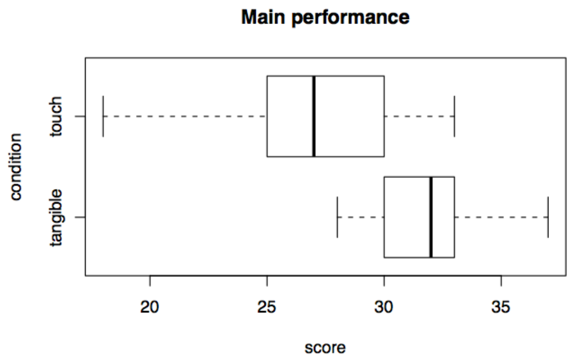


Figure 7.10: Study 3: box plots of the performance (number of shelves) for the tangible and the multitouch conditions (*p*<.001).

Results

The results confirmed the main hypothesis: participants in the tangible condition performed better than in the multitouch condition, $t(32)=4.873$, $p<.001$, they thus built warehouse layouts containing significantly more shelves (Figure 7.10). Regarding the efficiency of the warehouse (average distance from docks to shelves), dyads in the tangible condition (N=19, mean=14.8, SD=3.96) tended to design more efficient warehouses than the touch condition (N=15, mean=17.3, SD=4.51), $t(32)=-1.73$, $p=.09$.

The learning gain, measured by the pre- and post-tests, was computed for each subject by subtracting the pre-test performance from the post-test. A multi-level analysis was performed, following the procedure proposed by [Kenny et al., 2006] for dyadic analysis with undistinguishable members and independence within the dyad. Descriptive data are m=.43 (SD=5.4) and N=44 for the tangible condition, and m=-2.5 (SD=5.9) and N=34 for the touch condition. The multilevel analysis with the group ID as a random factor yielded a significative effect, $F(1.37)=6.68$, $p<.05$, which confirms the hypothesis that the tangible interface would have a positive impact on learning gain (Figure 7.11).

Secondary results: mediatory variables Table 7.3 reports the results obtained for the three mediatory variables measured in this experiment. It appears that apprentices explored significantly more alternative solutions in the tangible condition than in the multitouch condition ($p<.001$). The tangible interaction modality was also considered more playful ($p<.05$) and the collaboration was better in this condition than with the multitouch interface ($p<.01$). The ratings of the collaboration quality were confirmed by a second judge who rated 20% of the dyads. An inter-reliability analysis using Krippendorff's alpha was .93 [Hayes and Krippendorff, 2007].

The influence of the mediatory variables on the performance was then computed

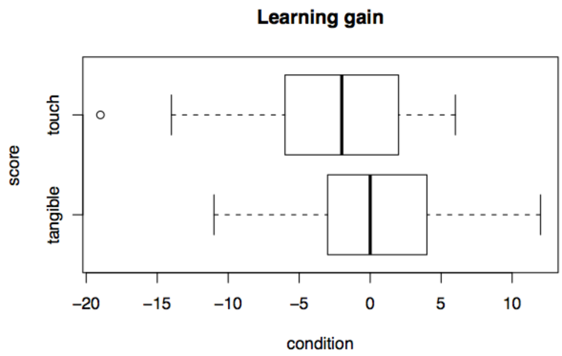


Figure 7.11: Study 3: box plots of the learning gain for the tangible and the multi-touch conditions ($p<.05$).

Mean (SD), t-test-values and effect sizes			
	Exploration	Playfulness	Collaboration
Tangible	196.18 (72.9)	80.2 (6.9)	32.1 (4.3)
Touch	130.35 (28.6)	76.2 (8.7)	27.2 (4.9)
T-test	$t(37)=3.86$	$t(76)=-2.2$	$t(37)=3.1$
Cohen's d	1.19	0.51	1.06
Sig	$p<.001$	$p<.05$	$p<.01$

Table 7.3: Study 3: mediatory variables.

using the method proposed by [Preacher and Hayes, 2008]. Results for multiple mediation showed that only exploration (CI: [0.02; 1.13]) was a mediator for performance. Further analysis performed on each condition showed that collaboration ($r=.57$, $p<.05$, N=17) and playfulness ($r=.53$, $p<.05$, N=17) were strongly related to a better performance in the touch condition. Only exploration turned out to be a significant mediator in the tangible condition ($r=.47$, $p<.05$, N=22).

7.1.4 Discussion of Phase 1 studies

These three studies confirmed the potential of the tangible approach in the context of the apprenticeship in logistics.

The observations conducted in classrooms of apprentices solving problems in the traditional pencil-and-paper context illustrate an aspect of the abstraction gap. Many apprentices do not have the necessary metacognitive and problem-solving skills to engage in this kind of activities. Solving a warehouse layout problem on paper leaves too many options open: this is the reason why most of the groups we observed spent a lot of time stuck in front of the problem, without knowing where to start. The solutions that they finally manage to produce are usually of a poor quality and reflect the difficulties apprentices face when they try to develop them.

The two layout examples presented in the study description clearly demonstrate the difficulties apprentices have in translating their experience into design rules and strategies. The layout made of squares (Figure 7.3) is a theoretical solution: apprentices computed the correct surfaces of each room, but were not able to translate these values into a consistent warehouse shape. The second example shows the opposite case (Figure 7.4): the warehouse is equilibrated, the size of each part is coherent with a typical layout but does not correspond to the constraints given in the problem statement and strong inconsistencies can be found among numerical values. These inconsistencies show that apprentices are not able to interpret the information presented on a 2D blueprint. Our hypothesis is this abstract representation is not linked with a real warehouse: they are not able to reconstruct it from the drawings and use it as an object on which they can think. This is confirmed by the fact that they do not use sketching to refine a potential solution. To use this technique efficiently, they should be able to use their sketches as external representations of the solution they have in their mind but do not seem to be able to do it. Pencil-and-paper activities are thus not adapted to the needs of these apprentices.

This first study uncovered the potential of the tangible approach in the context of the abstraction gap. The concrete representation offered by the tangible artifacts seemed to be better adapted to the skills of the apprentices who were able to engage immediately in the activity. Our observations have shown that they were able to interpret the small-scale model as a real warehouse and use it to detect potential problems. Teachers were surprised to see that some apprentices who are usually passive at school were actively participating to the problem-solving task.

Study 3 confirmed in a controlled setting the importance of tangibility in the ability of apprentices to work on warehouse layout problems. The comparison of the tangible interface of the Tinker Environment with a functionally equivalent multitouch interface showed that apprentices better solve this type of problem in the tangible condition. They also obtained a better learning gain. The participants in the multitouch condition even performed worse at the post-test than at the pre-test, which can be explained by the higher difficulty of the post-test. Among the three mediatory variables measured during the experiment (exploration, collaboration and playfulness), only exploration yielded a significant intermediary effect. Exploring more solutions is thus a good predictor of the performance in this warehouse layout task. Even though they didn't play a significant role in the score, collaboration quality and playfulness level were increased by the TUI.

The second study was useful to identify a central factor enabling a higher level of exploration in the tangible modality. It demonstrated that participants were significantly faster at physically manipulating objects than with the multitouch modality. Exploring different layouts with the TUI takes less time and thus allows apprentices to test more options. There is no definitive answer explaining the better learning outcomes in the tangible condition. We can easily conceive that a higher level of exploration leads to a better performance, but learning is less directly understandable. It might be due to the fact that it allowed apprentices to observe more examples of layouts which made it easier to generalize some general rules regarding the quality of a warehouse layout. Another hypothesis is that the tactile feedback provided by tangible artifacts allows apprentices to allocate less cognitive resources to the manipulation of the interface and focus more on the resolution of the problem.

It is fair to recognize that the difficulty of the task in Study 1 was much lower in the tangible condition and explains some of the differences we observed such as the time needed to complete the task, but it was not too easy either. The solutions proposed with the tangible interface were usually not of a better quality. Groups of apprentices did not plan their layout and were unable to consider the warehouse from a global perspective. This explains why we observed mainly local exploration of the solution space, with apprentices placing one shelf after the other without considering the big picture. This problem confirms the difficulties faced by apprentices in complex tasks, but also the typical limitation of TUIs in educational contexts pointed out in Section 2.5. The concrete representation of the tangible artifacts, combined with the apparent facility they offer to complete the task, resulted in the tendency observed among apprentices to stay at a concrete level of reasoning. They focused on trial-and-error strategies without taking the time to reflect on the activity and plan at a higher level of abstraction.

Another interesting observation made during Study 1 is that the Tinker Environment implies more improvisation for the teachers. They can no longer plan the outcome of the activities they organize during the class. The result as well as the events that occur during a warehouse layout task are unpredictable, and the teachers have to use them to address the concepts they want to teach. Teaching on the fly requires to detect particular events like misunderstandings, errors or ideas proposed by apprentices and use them as learning opportunities. The teachers did that on a regular basis during the study, linking the context of the activity to the corresponding logistics concepts. They told us during post-class interviews that it was challenging for them to find the right degree of control of the activity: they have for example to decide how long they should let a group go in the wrong direction before interrupting them. Interrupting too early prevents the apprentices from finding the error by themselves; interrupting too late may anchor misconceptions. This is an old issue in education that is made salient because teachers face an unfamiliar situation.

Teachers also have a crucial role to play to encourage apprentices to reflect about their solutions. The fact that the small-scale model allows apprentices to solve a warehouse layout task much faster than in the traditional pencil-and-paper condition represents an interesting opportunity for teachers. It gives them the time to discuss the proposed solutions, point out their limitations and encourage apprentices to think about a better approach before implementing a new layout. This point is addressed in more details in Study 4.

7.2 Phase 2: Addressing the scalability issue

The two DBR studies reported in this section relate to the development of a complementary interface to the warehouse small-scale model. The need for such an interface is directly related to the discussion on the scalability issues of TUIs in Section 2.5. The small-scale model offers a limited set of possible actions to teachers and apprentices (add, remove and move objects). It offers a rich and natural way to layout warehouses but needs to be completed to control intangible aspects of the logistics simulation. Study 4 encompasses trials made with different types of unsatisfactory solutions which are useful to better understand the benefits brought by TinkerSheets. Study 5 reports observations conducted in classrooms after the introduction of the TinkerSheets. It describes their impact on the use of the system at the individual and group levels.

7.2.1 Study 4: early solutions to the scalability issue

This study gathers together the different strategies that have been implemented in the early developments of the Tinker Environment to accommodate a real use of the system for logistics teaching. The need for a separate interface to control intangible aspects of the software, such as the simulation (start/pause/stop), its speed or the visualizations displayed on top of the small-scale model, became soon clear after the first sessions in classrooms. As already discussed in Section 2.5, adding more tangible objects to a TUI to control an increasing number of parameters is not sustainable beyond a certain point: the interactive space reaches its limits and it becomes too difficult for users to interact with the system since they spend too much time looking for the right artifact. We now review the different solutions that were implemented before the TinkerSheets. Each approach is first described from a functional point of view and is then discussed based on observations of teachers and apprentices using it. While there were obvious flaws in most of the implementations presented here, they were nonetheless useful to learn key lessons that go beyond pure usability questions to more general system architecture and adoption questions.

Marker-based scenarios

The first way to control the simulation running on the TinkerTable was done by showing specific fiducial markers. Each marker was printed on an paper sheet with a short text explaining its functionality. Pedagogical scenarios were implemented by stapling together several pages corresponding to different parts of an activity. The Tinker Environment was used by teachers and their apprentices very early in the development process, when it only implemented a basic set of functionalities. Teachers could choose among two scenarios (warehouse layout and navigation optimization) that were subdivided in different phases that had to be followed in sequence. Selecting a scenario and moving from one phase to another was done by turning the pages of this simple booklet.

Observations The marker-based interface was tested with the TinkerTable when it was used for the first time by the teachers. The session took place on our university campus because the system was not yet installed in a professional school.

Two different scenarios had been prepared to be used by the teachers. The first one was a warehouse layout activity, similar to the task described in Study 1. The teachers added some complexity by placing architectural constraints in the form of metallic pillars in the warehouse. The objective of this scenario was to allow the apprentices to think about warehouse design and then discuss the advantages and/or drawbacks of their solutions. The second scenario was a forklift move optimization activity where apprentices had to find the optimal sequence of moves to get a certain number of pallets from the reception dock to given positions in the storage area and get the same number of pallets from the storage area to the expedition dock. The pallets and their positions were randomly selected by the system and the scenario could be played on any warehouse layout which allowed the teachers to reuse the solutions obtained during the first activity.

The marker-based approach was not satisfying. For the teachers, showing a marker to a camera was not an intuitive way of interacting with the system and they would often get confused about what they were supposed to do to move to the next phase. The concept of a scenario was not appropriate either, as they preferred to organize their course in a more flexible way which did not necessarily follow the predefined phases.

Screen-based menu

In the next prototype, we implemented a screen-based hierarchical menu that was operated by a keyboard. This menu was displayed as an overlay over the projection of augmentations which consequently were partly hidden when the menu was open. This menu gave access to several commands and parameters, including a set of visualizations, simulation control (start, run and pause) and speed.

Observations Trial sessions were conducted with two teachers and showed that this approach was not appropriate. To use the menu, teachers were obliged to move to the computer, press a key and then navigate to the option they wanted to set. This was disrupting the interaction with the class and teachers often got confused with the hierarchical organization of the menu, forgetting about the exact position of a given option. Moreover, teachers often forgot to close the menu after using it, thus leaving the projection on the tabletop partly occluded. Another unwanted effect of this screen-based menu is that it was implicitly reserved for teacher use. Apprentices did not dare to use the computer to change a parameter as it was perceived as a teacher tool that they were not allowed to use. The usability issues could have been corrected with a better design of the menu, but its negative impact on the interaction convinced us to develop another approach.

Finger-based menu

We tried to overcome these limitations with a third prototype that implemented a tabletop menu controlled through fingertips. This menu used the infrastructure of the TinkerTable to draw an augmented icon-based menu on a (blank) sheet of paper. Users could select an icon by pointing to it with their finger, which was detected by the system's camera. A simple algorithm was used to detect the presence of a finger on an icon: the part of the image corresponding to the position of the icon is extracted and thresholded, and the presence of a finger is checked by looking for an elongated shape with an extremity close to the center of the icon. This finger-based menu implemented the same set of functionalities as the screen-based menu.

Observations With this approach the system became mainly operated by the apprentices who felt more at ease with this interaction modality than their teachers.

Our implementation suffered from several flaws due to the technical setting of the TinkerTable: using the image from the ceiling camera as the unique input for controlling the menu did not allow the system to detect when a user was touching the table surface and resulted in too many false-positive detections. Teachers did not feel in total control of the system and were thus not willing to interact with it.

Study 4 conclusions

These successive design iterations allowed us to observe the main difficulties that our users were facing with different input modalities. As the needs for a way to control parameters and visualize simulation data were increasing, we progressively defined the main requirements of the interface that would fit the constraints of the hardware setting of the Tinker Environment and allow teachers and apprentices to interact with these more abstract aspects of the environment. This eventually led us to the design of the TinkerSheets which are described in the next section.

7.2.2 Study 5: TinkerSheets

Observations

The TinkerSheets were tested with six groups of 2 or 3 apprentices in the second year of their apprenticeship (N=15) and two teachers in their classrooms at the professional school in Thun. This was the first time that the apprentices worked with the TinkerLamp and the TinkerSheets. The teachers already knew the system and participated in the design of the TinkerSheets used during these sessions, but were using them for the first time during a class.

Class objectives The goal of the class was to introduce the different types of surfaces that are defined in a warehouse:

- *Total surface*: the surface of the full warehouse footprint;
- *Raw storage surface*: the total surface from which secondary areas are removed, such as offices, technical rooms and toilets;
- *Net storage surface*: raw storage surface without the alleys, which corresponds to the cumulated surface of shelves in the Tinker Environment.

The second objective was to illustrate the influence of the type of forklift on the net storage surface available in a warehouse: a larger forklift needs wider alleys, and hence leads to a smaller net storage surface. General instructions and three TinkerSheets were available to support these pedagogical objectives. The design of the sheets was discussed and agreed upon in close collaboration with the teachers during a meeting that preceded the training sessions.

Material Two TinkerLamps were installed in the back of the classroom, allowing two groups of apprentices to work in parallel. Complementary pencil-and-paper exercises were assigned to the other apprentices who were doing them in the class as well. The activity on the Tinker Environment involved three different Tinker-Sheets, a master sheet and two companion sheets.

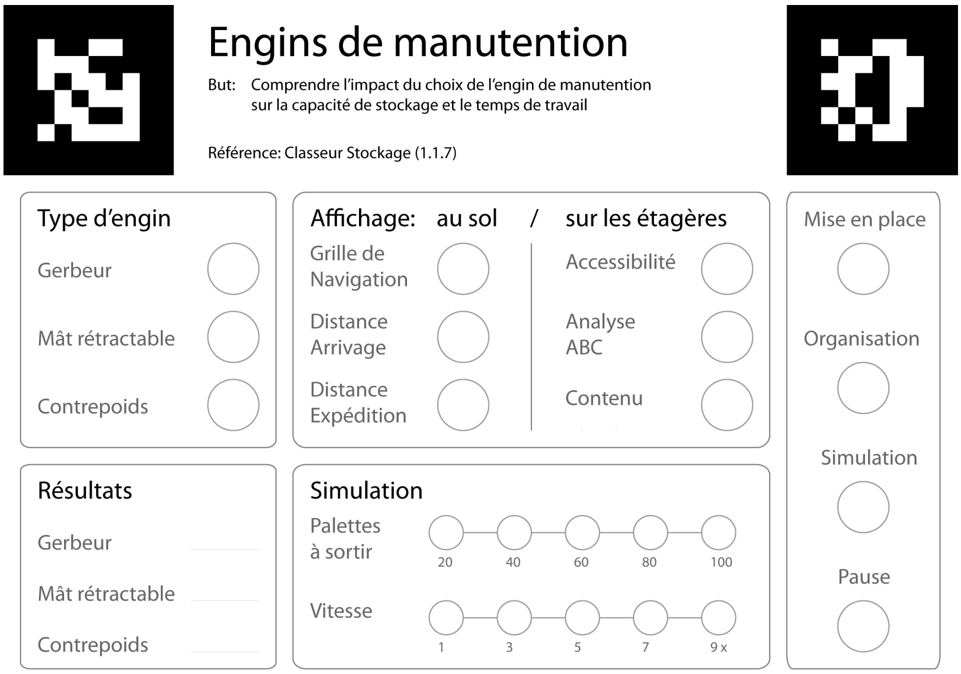


Figure 7.12: Study 5: The master sheet used during the sessions. It allows to control the simulation and set the relevant parameters for the topic of the lesson.

The *master sheet* (Figure 7.12) allowed to switch among three simulation states (layout, organization and simulation). Organization is an intermediary state where the elements of the small-scale model can be added and moved as usual but can not be deleted. It allows users to ensure that all the elements have been correctly detected by the system before running a simulation. The master sheet also includes controls for the duration of the simulation (number of pallets to move) and its speed, the type of augmentation displayed on the shelves and on the warehouse floor, and the type of forklift used during the simulation (three types of increasing sizes which require larger alleys).

The two *companion sheets* used in this activity were the *surface sheet* and the *process sheet*. The *surface sheet* (see Figure 6.7 on page 90) was designed to illustrate the three types of surfaces numerically and graphically. The numerical output consisted of the total, raw and net surface expressed as square meters and percentages. The graphical output illustrated the surfaces through the projection of a reduced and colored version of the warehouse. Users were able to switch between the visualization of raw and net surfaces. It is worth noting that the graphical representation exactly matched the schema which is used in the corresponding course material. The *process sheet* displayed numerical information about the content of the warehouse (number of shelves, number of available storage spaces and percentage occupied) as well as about the current state of the simulation (total number of pallets to move, number of pallets moved since the beginning of the simulation and average time to move a pallet).

Lesson plan The lesson consisted of a planning phase, an implementation phase, followed by series of testing phases and finally by an exploration phase. One of the teachers stopped the activity after the testing phases because of time constraints (two groups). The activity was inspired by a pencil-and-paper activity that teachers used to do with their apprentices, where they asked them to draw the blueprint of the school's underground parking and layout a warehouse in it. The activity was adapted to match the constraints of the Tinker Environment in terms of warehouse surface and shape and extended into a lesson plan that takes advantage of the environment.

1. Planning phase (45 minutes): Apprentices were instructed to draw a blueprint of a warehouse on paper. This phase corresponds to the traditional pencil-and-paper activity described above. They were given the scale of the drawing (1:50), as well as the size of the shelves, docks, and administrative area. They first had to place pillars, loading docks and an administrative area. The drawing of these elements defined the architectural constraints. The next planning step consisted of drawing shelves in a way to maximize the net storage surface.

2. Implementation phase (5 minutes): Apprentices put their blueprint under the TinkerLamp and placed the tangible docks and shelves on the locations they had drawn. The length and width of the administrative area were purposely constrained by the teachers to match the space necessary to place the master sheet which allows to control the simulation.

3. Testing phase (5 minutes): Once all shelves were placed on the blueprint, apprentices used the master sheet to start a simulation of the warehouse (Figure 7.13). The goal of this simulation was to assess the quality of the layout, which could be obtained from the information displayed on the surface and process companion sheets. They then wrote down the result of their initial design and moved on to test the next apprentice's design (two groups of 5 apprentices compared their designs like this and did not move on to the exploration phase).

4. Exploration phase (30 minutes): Four smaller groups of 2 to 3 apprentices implemented alternative warehouse designs by tinkering with the spatial arrangement of shelves. Each alternative design was tested by starting a new simulation and checking results with the surface and process companion sheets. When they thought that they reached the best possible result, apprentices used a pencil to fix the solution on the blueprint by outlining the edges of the shelves.

Results

This study confirmed the potential of Interactive Paper Forms (IPFs) as a complementary interface to TUIs. We observed that both teachers and apprentices were at ease with the use of TinkerSheets. While teachers already knew the interface, apprentices discovered it at the beginning of the activity but a very short explanation and a demonstration were enough for them to use it without difficulty. Apprentices did not appear to be surprised or intrigued by the fact that a sheet of paper could be

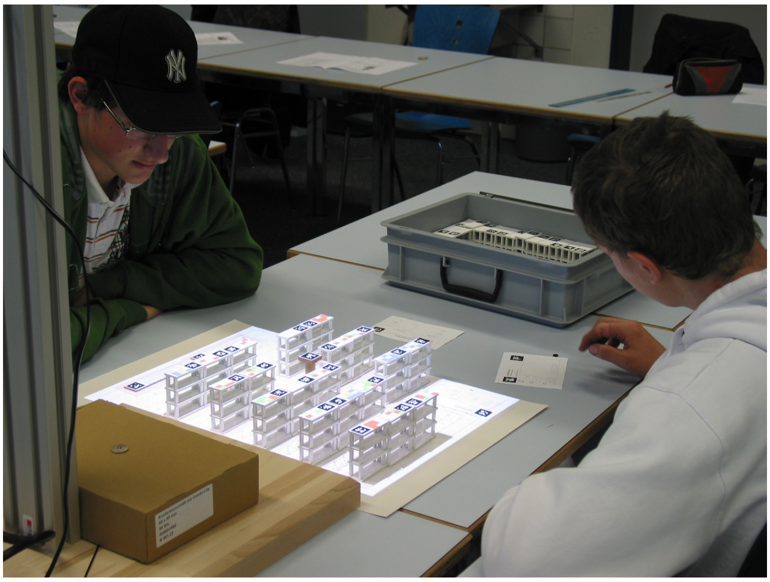


Figure 7.13: Study 5: Apprentices at work. Companion sheets are placed next to the simulation.

used to control a computer application, an interaction modality they never encountered before. We expected some comments and reactions during the explanations of teachers but they were almost inexistent. These observations confirm the power of the form metaphor which brings a strong level of intuitiveness to TinkerSheets. Compared to the interfaces presented in the previous study, both teachers and apprentices were at ease with the interface. The calibration of the system was not always perfect and it would thus not detect tokens placed precisely on top of an interface element. Apprentices, and more importantly teachers would then simply try to move the token around until the system would detect it. While the erratic behavior of the finger-based menu was enough to prevent teachers to use it, these detection problems did not affect their confidence in the system. False negatives seem to be better accepted than false positives: getting the system to *see* something is more predictable, keeps the control on the user side and thus reduces anxiety compared to a system that performs unwanted actions.

Manipulation A closer look at the interactions with the TinkerSheets confirmed the fact that IPFs support a less direct interaction modality than TUIs. Placing a token on a sheet was usually performed with two-hands: one to position the token on an interface element and the other to avoid that the sheet moves. Some users used the tip of a pencil to displace a token because of the relative small size of the TinkerSheets (A6 paper) and the precision needed to position tokens. Occlusions sometimes posed problems to some apprentices who tried to interact with TinkerSheets partially occluded by other sheets. While these issues probably disappear with some experience with the system, they show nonetheless that a minimum of care has to be taken when manipulating the interface which forces users to temporarily switch away from their main task. This is again in line with our expectations that IPFs represent a trade-off between directness and scalability.

This first DBR study with TinkerSheets confirmed the potential of the approach to control the tangible simulation developed for the Tinker Environment, as well as the limitations of this Paper User Interface (PUI). It also allowed us to observe some of the advantages offered by the affordances of paper, during the activity but also during its preparation with teachers. We report these observations in the following paragraphs, each addressing a specific expected property of IPFs.

Figure 7.14: Study 5: An apprentice carefully stacking a Companion sheet on top of the Master sheet.

Spatial arrangement and persistence At the beginning of the class, teachers placed the TinkerSheets next to the TinkerLamps. The printed content of a TinkerSheet makes it persistent: it is possible to understand the functionalities it offers without placing it in the interactive area of the system. Apprentices took advantage of this possibility: they left the sheets on the side of the interactive area and spatially arranged them to have a global view of the available parameters and visualizations. Compared to a menu which hides available options and obliges users to go through submenus to find them, TinkerSheets allowed apprentices to get a global view of the system and access functionalities much faster. This is particularly important with users like these apprentices who are not and do not have to become experts of the system. While progressing through the activity, apprentices placed sheets in the augmented area whenever needed: they chose the *surface* sheet to measure surfaces and the *process* sheet to measure warehouse efficiency during simulations.

Stackability, monitoring and lookup We also observed apprentices who stacked TinkerSheets on top of each other (Figure 7.14), even if some tokens were placed on one of them. This is possible because tokens are thin, such that even though

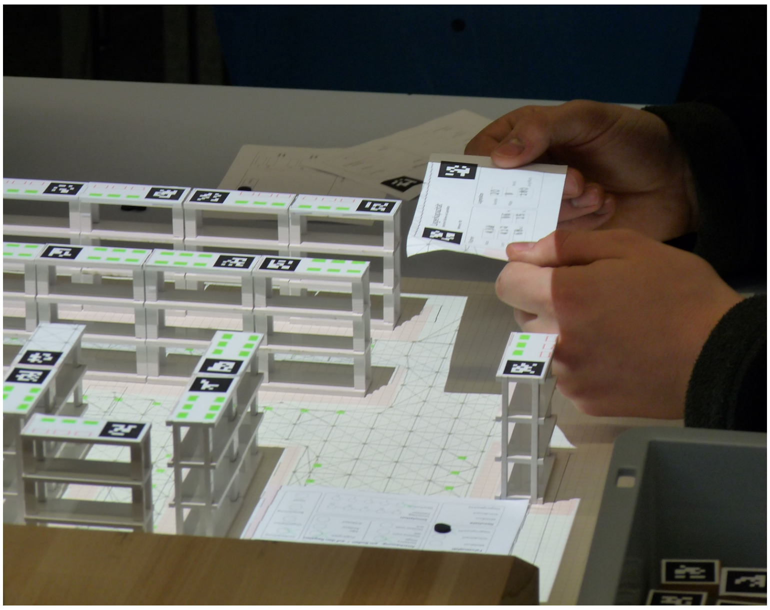


Figure 7.15: Study 5: An apprentice quickly placing a lookup TinkerSheet below a TinkerLamp to check a value.

TinkerSheets are calibrated to be used on the surface the digital information is still well aligned with the printed content after stacking several sheets. While stacking saves space on the limited interactive surface, it also limits the visibility of TinkerSheets and makes their retrieval more difficult. This is particularly salient in a collaborative environment because the user looking for a particular sheet might not have noticed that a peer had stacked another sheet on top of it. Another problem that was observed with this behavior is that tokens situated below a sheet were often moved when the upper sheet was removed. To circumvent this problem, several groups avoided stacking sheets by using sheets in two different ways: monitoring and lookup. *Monitoring* sheets were placed in the interactive area and stayed at the same position for an extended period. Apprentices used them to keep some interface elements always available, such as often used parameters or feedbacks that need a constant attention. *Lookup* sheets were left on the side of the interactive area and brought under the camera's field of view only for quick checks (Figure 7.15). The surface companion sheet was typically used as a lookup sheet since it was sufficient for apprentices to know the exact value from time to time only. The process sheet was more used as a monitoring sheet since apprentices wanted to have a continuous view of the evolution of the simulation.

Implicit roles We observed that apprentices tended to specialize in different roles. In a group, some members were mostly involved in the warehouse layout tasks while others were monitoring values on TinkerSheets. Our impression was that apprentices tended to specialize in a given role based on their position around the environment and their proximity to the interface elements. We tested this qualitative observation with a quantitative analysis of eight groups working with the

Tinker Environment during the sessions described in this study. Five groups were dyads and three groups were composed of three apprentices. We used the video recordings of these sessions to count the number of actions performed among these groups. The distance between the apprentice and the interface element on which each action was performed was coded as near or far. The interactive area was partitioned in four quarters (Q1 to Q4) and apprentices seated at three positions (U1 to U3), as shown by Figure 7.16. Actions of users were coded as near for the two quarters close to them (e.g. Q1 and Q4 for U1). Five types of actions were coded. Four were related to the warehouse small-scale model: Add, Move, Adjust (fine-tuning of the position of an element) and Remove. One concerned actions on TinkerSheets (placement of a token). The results are shown in Table 7.4.

There is effectively a clear tendency by apprentices to interact mostly with interface elements situated closer to them. This effect is particularly strong in the case of TinkerSheets. Among the 241 actions performed on TinkerSheets, only 16 took place on a sheet located far away from the position of the apprentices who issue them. These results thus confirm that apprentices tend to take implicit roles based on their position around the table and the proximity of interface elements.

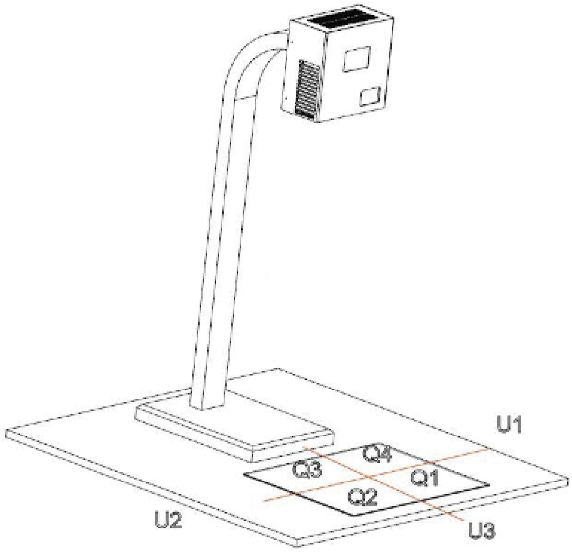


Figure 7.16: The partitioning of the interactive area projected by the TinkerLamp. U1 to U3 represent positions of apprentices and Q1 to Q4 are quarters used to code the distance of actions performed by apprentices.

Co-design The paper nature of TinkerSheets and the persistence offered by their printed content also proved to be important for the involvement of teachers in the preparation of the activity. During a meeting which took place at the professional school cafeteria, teachers numbered and annotated the TinkerSheets to structure the lesson and imagine how and when they would use each of the sheets (Figure 7.17). Annotations were also used to write down some modifications proposed by

	Add	Move	Adjust	Remove	Sheet
Near	282	289	366	261	225
Far	108	112	125	66	16

Table 7.4: Number of actions given the type of action and the proximity of action for eight groups of 2 to 3 apprentices working with the Tinker Environment.

the teachers. The sheets allowed the discussion to take place at a concrete level: the activity was simulated by actually looking at and drawing on the interface. It made it easier to uncover missing elements on the sheets and allowed teachers to actively participate in the design of the interface that they would have to use. Before the TinkerSheets, meetings like this one tended to stay at a rather general level, researchers and teachers agreeing on the general organization of the activity without considering practical aspects.

Figure 7.17: Study 5: Two teachers and a researcher designing the master and companion sheets.

7.2.3 Discussion of Phase 2 studies

The two DBR studies reported in this section concerned our efforts to develop an adapted interface to control and visualize the simulation running on top of the warehouse small-scale model of the Tinker Environment.

Lessons learned from Study 4 Study 4 reviewed three different interaction modalities which failed in different ways. The different problems encountered by these approaches were useful to uncover the qualities needed by a good complementary interface to the TUI.

The *fiducial marker-based scenarios* that were used in the early days of the system were not adapted to the needs of the teachers. They were useful to demonstrate the importance for teachers to maintain the control on the behavior of the simulation. They illustrate again the discussion on the new role of teachers identified in Phase 1 studies. This interface also suffered from usability issues: they were not intuitive at all for teachers to use. The lack of feedback made it difficult for them to know at which step of the scenario the simulation was. Another possible reason is that it was not clear from the information printed on each scenario step what would exactly happen, and teachers did not feel confident enough to move from one step to the other.

The *screen-based menu* faced two main issues: it was disconnected from the rest of the environment and was exclusively used by teachers. The disconnection issue comes from a physical distance between the central interaction space, which is the warehouse layout on the interactive area, and the control space on the computer screen. This physical separation introduces a break in the interaction flow since someone, in this case the teacher, has to move from the table to the screen and control the menu with the keyboard. Beyond the usability issues of this menu, which could have been overcome with some work, and the physical separation, which would have disappeared with the TinkerLamp, this interface creates a distance that comes from its intrinsic different nature. While the TUI supports collaborative interactions and makes actions of group members visible to the others, the screen-based menu is a single-user interface. In the implementation tested with apprentices, the menu was displayed both on the screen and on the table and thus prevented the rest of the group to continue working on the task. Another option would be to display it on the screen only, but the actions would then be invisible to the rest of the group. The single-user interaction modality of this interface was made worse by the social constraints of the classroom: the computer is a tool usually reserved for the teacher only and hence prevented apprentices from using it.

The *finger-based menu*, finally, tried to overcome the limitations of the screen-based menu by keeping the input and output collocated. Despite this advantage, technological constraints did not let us implement it in an acceptable way and usability issues convinced us to abandon it. An option could have been to use tangible tokens to select menu items, like for TinkerSheets, but our hypothesis after implementing the TinkerSheets is that it would have suffered from scalability issues. Its purely digital nature would have obliged users to know the tree structure of the menu it in the same way as they would in a GUI menu, an approach more difficult than the solution finally adopted, the TinkerSheets.

Impact of TinkerSheets Study 5 reported our first observations of the user of TinkerSheets in a real classroom context. Compared to the interfaces previously implemented for the Tinker Environment, they were adopted by both teachers and apprentices who understood immediately how to use them and were not blocked by some detection issues with the first version of the software. We have seen that apprentices developed different ways to handle the sheets, arranging them for example next to the interactive area or stacking them on top of each other. The paper nature of the TinkerSheets certainly played an important role in this quick adoption of the interface since it corresponds to a typical use of traditional paper documents. This illustrates how the intuitive knowledge and habits people have of paper are easily transferred to this novel usage.

TinkerSheets also allowed to integrate interactions with the Object of Interest (OoI) and secondary interface element into a single space, which limits the time needed to switch the focus of attention from one element to the other. As expected, the interactions with the sheets are rather indirect and take more time than actions on the small-scale model. This didn't seem to bother apprentices since most of their actions took place on the tangible elements. The different strategies that they implemented to handle TinkerSheets (i.e. monitoring and lookup sheets) reflect a natural tendency to optimize their use of this more indirect interface. Monitoring sheets, which are used more often, are left at fixed positions but lookup sheets, which are needed for quick checks are left on the side of the interactive area where they can be quickly reached. Apprentices thus artificially augment the size of the system, using the space around the interactive area to store inactive sheets. Their printed content allows them to exist out of this area and lets apprentices quickly find them, either through visual recognition or by remembering where they placed them. The physicality and readability of the interface away from the digital system was also experienced in the co-design session with teachers. As pointed out in the study report, it allowed us to prepare in a more complete way the session with the teachers.

This study also identified possible improvements of the TinkerSheets. The fact that several groups stacked sheets on top of each other is the consequence of a competition for space between the warehouse small-scale model and the PUI. In the activity, the whole interactive space was dedicated to the layout of the warehouse. Apprentices sometimes had difficulties to find space where they could place a TinkerSheet, especially towards the end of the layout phase where the warehouse was full of shelves. Some groups found interesting tricks to get round this issue, such as placing sheets on top of shelves during simulations (Figure 7.18), but a better organization of space is needed.

7.3 Phase 3: Towards abstract representations

This phase corresponds to the implementation of the pedagogical approach outlined in Section 5.2. Briefly stated, it proposes to overcome the abstraction gap through a progressive move from concrete to abstract representations, supported by the use of Multiple External Representations to enable smooth transitions between one level and the next. The introduction of the TinkerSheets in the Tinker Environment made it possible to implement this approach. The 2D display they offer permit the presentation of more abstract, complementary representations to the warehouse small-scale model. The TUI serves as a real-world anchor, providing apprentices with a representation of the warehouse as they experience it at the workplace. The TinkerSheets complement it with the same information represented in a less embodied way, closer to the typical way theoretical concepts are presented at school.

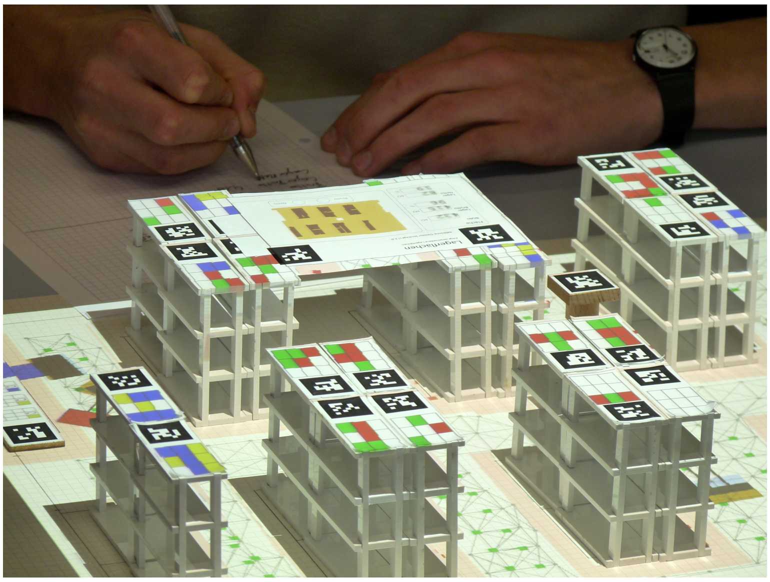


Figure 7.18: Study 5: Example of a trick found by apprentices to overcome the space limitations of the interactive are: a TinkerSheet placed on top of shelves during a simulation.

The three studies presented in this phase cover three typical activities taking place at different stages of the apprenticeship in logistics. They illustrate the progression from concrete to abstract representations at two levels: local, within a single activity through the use of MERs, and global, through a progressive move from concrete, embodied problem-solving activities introducing relatively basic concepts towards more complex notions presented on more abstract representations of a warehouse. Each study corresponds to a specific classroom observation session, reported in three parts: we first give an overview of the activity, explain how MERs are used and finally describe our observations.

7.3.1 Study 6: Alley width

Description

This session took place on a TinkerTable and a TinkerLamp with a class of first-year apprentices. The goal of the activity was to let apprentices discover the influence of different forklift types on alleys' width. Choosing a forklift is a trade-off between speed and storage space: a smaller forklift is slower but can drive in narrower alleys than bigger forklifts which reach higher speeds but need more space. A bigger forklift may also be able to handle heavier boxes and store them in higher shelves, thus compensating for the storage space lost because of larger alleys. The first part of the activity was a typical warehouse layout task, already encountered in previous studies. During this activity, the top of the shelves was augmented with information about their accessibility (described in Section 6.5.1). This representation is the result of several design iterations trying to disambiguate the fact that a shelf is accessible

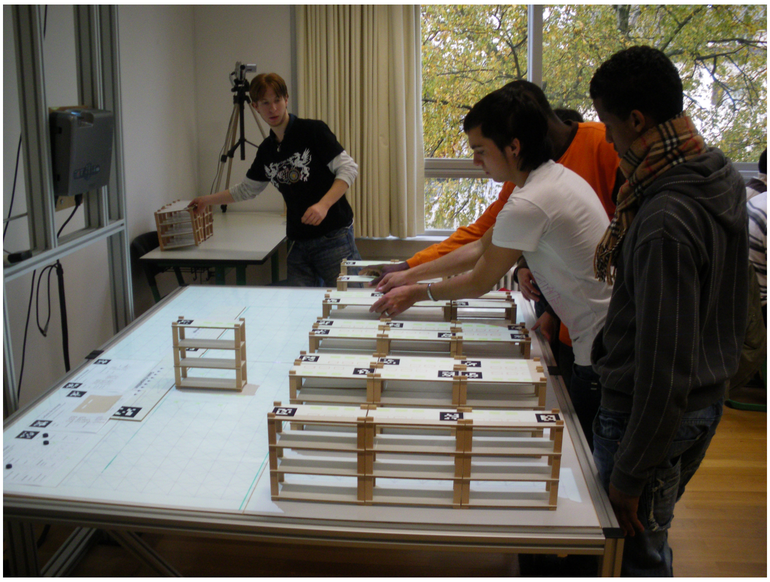


Figure 7.19: Study 6: Apprentices layout a warehouse while respecting a fixed shelves orientation.

from both sides, which did not appear to be obvious for many apprentices.

Lesson plan The lesson plan guides apprentices in the discovery of the relation between forklift type and alley width. In the first part of the activity, groups of apprentices were instructed to use the small-scale model to design the layout of a warehouse, placing as many shelves as possible in a given area of the table, with the additional constraint that shelves' orientation was fixed (Figure 7.19). When apprentices were satisfied with their design, they wrote down the number of shelves and accessible boxes. They were then asked to repeat the same task with the two other types of forklifts. After completing the task, each group sat around a table in the classroom and tried to deduce some conclusions from their results. At the end of the session, the teacher organized a debriefing session where the conclusions of each group were discussed.

Available TinkerSheets Two TinkerSheets were used during this activity. The first one allowed apprentices and their teacher to choose among three types of forklifts while the other displayed the number of shelves and accessible boxes in the warehouse.

Use of MERs

In this case, we have two types of representations for the number of shelves: the visible amount of shelves on the table and the number written on the TinkerSheet. In addition, the TinkerSheet displays the number of accessible boxes. The augmentations allow making explicit the precise numbers corresponding to the intuition of quantity that is obtained by observing the 3D model.

The number of accessible shelves is represented in three ways: the observable distance between shelves on the table (leading to comments like: *"it's ok here, you can go through with your forklift!"*), the red and green squares and triangles projected on top of the shelves (*"No, it's red now, move it away!"*) and finally through the difference between the total number of shelves and the number of accessible ones displayed on a TinkerSheet.

Observations

The obligation to place the shelves in a given orientation was difficult to respect for apprentices as they wanted to take advantage of different orientations to place as many shelves as possible in the available space. They perceived this rule as being arbitrary, which it actually was: respecting a fixed orientation was not natural for them as it had no reason to exist other than to illustrate the effects of forklift types on alley width and indirectly the storage capacity of a warehouse.

The difficulties we had to find a clear augmentation showing the accessibility of the shelves while clearly indicating that a shelf does not have to be accessible from both sides illustrates the difficulties some apprentices have when they enter the vocational training system. At the beginning of the session, the teacher placed a small-scale model of a box in a shelf to clearly show that a shelf is wide enough to contain only one box, such that only one of its sides has to be accessible. Even with the current augmentations, some apprentices still do not place shelves next to each other and insist on leaving both sides of the shelves accessible for forklifts. On several occasions, one member of a group pointed out that it was not necessary to leave space on both sides of shelves. Most of the time, these apprentices had repeated arguments with the rest of their group but did not manage to convince them. The teacher had to intervene to discuss this point with the group and get the apprentices to understand the inefficiencies that result from leaving both sides of the shelves accessible.

7.3.2 Study 7: Surfaces

Description

This second session took place on a TinkerTable and a TinkerLamp with a class of apprentices in the beginning of their second year. At this time, apprentices were reaching the end of the designer module (see Section 5.1). The objective of the activity was to introduce the different types of surfaces that are used to describe a warehouse and to illustrate the impact of a warehouse layout on work efficiency. In their curriculum, apprentices in logistics have to become familiar with three kinds of surfaces, already described in Section 7.2.2: the *raw surface*, the *raw storage surface* and the *net storage surface*. While these definitions seem to be quite simple, many apprentices have problems to remember them and are most of the time not able to make a rough estimate of their relative importance when presented with the blueprint of a warehouse. In a questionnaire we distributed to several classes asking apprentices to choose among four layouts printed on paper the one with the largest net storage surface, most of them gave a wrong answer. We also asked them to estimate the absolute value of this surface, the answers we received differed with more than one order of magnitude. The same was true for questions asking for percentages, with answers ranging from less than 10% to more than 70%.

Lesson plan This plan relies on a more exploratory learning activity, less tightly guided than during Study 6. The task of apprentices was to design a warehouse layout maximizing both the percentage of net storage surface and the work efficiency. In a first layout phase, they were asked to use only ten shelves, which correspond to a very low usage of the table surface. The teachers then discussed with them the surfaces corresponding to this amount of shelves and asked them to think about how they could augment the percentage of net storage surface. Each group was then given time to build a warehouse with as many shelves as they wanted and were encouraged to try different layouts. When apprentices were satisfied with a given layout, a simulation was run to test its efficiency. The goal of the simulation was to test how much time four forklifts would need to move one hundred boxes from the storage area to the expedition dock. During the simulation, the content of the shelves is projected on their top and is represented by colored rectangles corresponding to different product types.

Available TinkerSheets During this session, apprentices used the same TinkerSheets as for Study 5: a master sheet to control the simulation and two companion sheets, the surface sheet and the process sheet.

Use of MERs

Surfaces are represented three times in this activity: through the perception of the physical properties of the small-scale model (relation between space occupied by objects and table size), by a downscaled drawing on a TinkerSheet and finally numerically by absolute and relative numbers. The graphical representation on the TinkerSheet is the bridge between the specific area of the warehouse (highlighted in a different color, dark rectangles on Figure 7.20) and the numbers which represent it.

Observations

Several groups followed a surprising pattern during the initial layout phase. These groups placed the shelves as if they were gas particles, trying to maximize the distance between each of them and thus using the whole surface of the table even though a small fraction of it would have been necessary. They then read percentage of net storage surface on the TinkerSheet and observed that it was really low (below 10%). They tried to augment it by regrouping all the shelves in one corner of the table and were surprised to see that the number did not augment. A group member finally understood the reason why it did not change and could explain it to the others. While the intuition about grouping the shelves together has some valid ground (augmenting the density of the shelves augments their relative use of space), these groups failed to take into account the fact that the raw surface of the warehouse does not change whatever the position of the ten shelves. It illustrates the difficulty that apprentices have to cope with proportions and spatial relationships.

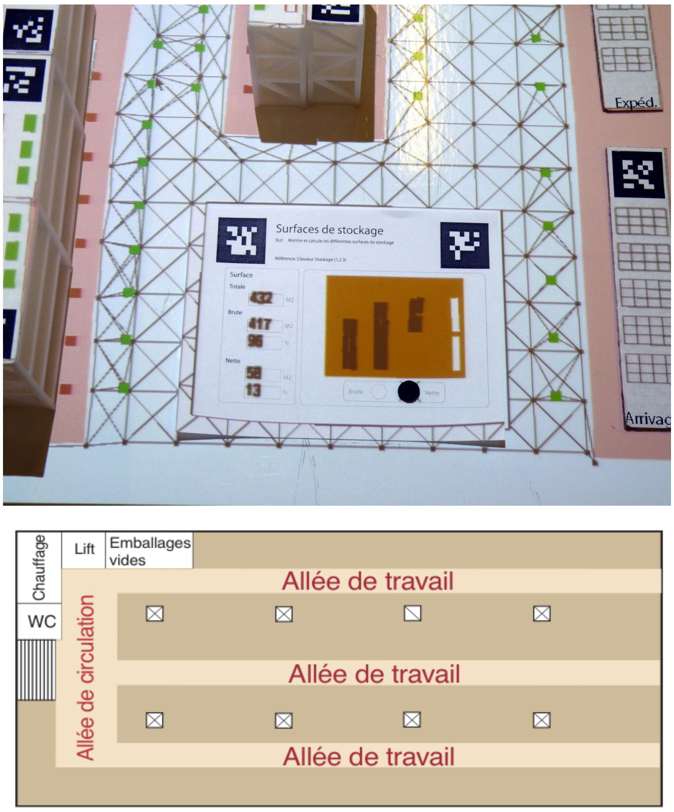


Figure 7.20: Study 7: Warehouse surface. Left: the *surface* TinkerSheet; it displays a scaled and colored view of the warehouse which illustrates the concepts of net and raw storage surfaces. Right: the schema presenting the net storage surface in the course book (dark parts represent the net storage surface, lighter areas are alleys and white rectangle stand for annex rooms such as administrative office, technical rooms or toilets).

7.3.3 Study 8: Storage management

Description

The third session took place on the TinkerTable with a class of apprentices in the middle of their second year. The objective was to introduce concepts related to storage management. Given a set of parameters including the annual demand for a given product and suppliers' delivery delays, apprentices were asked to define a restocking strategy minimizing the storage breaks. Two values could be modified by apprentices. The products reorder threshold (i.e. the product should be restocked if its amount in the warehouse goes below this value) and the size of product reorders (i.e. when a product has to be restocked, order this amount of pallets to the supplier). Figure 7.22 shows how these two concepts are illustrated in the learning material of apprentices.

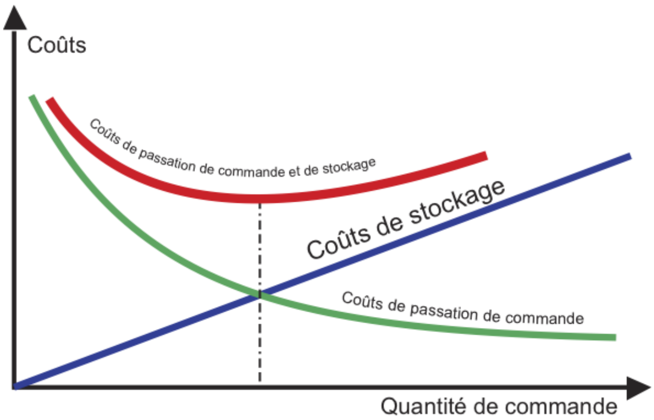


Figure 7.21: Study 8: This chart (taken from the apprentices' learning material) illustrates the concept of reorder threshold and optimal reorder quantity. The curve shows the evolution of the storage level. Whenever it reaches the horizontal line (reorder threshold), an order is issued to the suppliers for Q (optimal quantity) pallets. In this example the parameters are well defined: no storage break happens (red/dark area) and reaches the security level (orange/light area only on exceptional occasions).

The difficulty for apprentices is to understand how these values are related to external factors like customer demand and delivery time. If for example the suppliers' delivery delay becomes longer, the typical reaction of apprentices is to augment the size of reorders. This does not solve the problem because reorders are still issued when the amount of available pallets of a product reaches the same limit. As the reorder is delivered later, more pallets of this product will be ordered by customers in the interval between the reorder time and its delivery, resulting in storage breaks.

Another aspect that the teachers addressed during this session is the Andler formula which is used to compute the theoretical optimal reorder size, mentioned during the description of the curriculum's designer module (Section 5.1.2). This equation takes as input several parameters including the annual customers' demand, the fixed ordering costs, the storage costs and the price of a given product and computes the optimal size of reorders for this product. It computes an optimal trade-off between reordering and storage costs by finding the reorder size that minimizes their sum. Figure 7.21 shows a graphical representation of this formula as presented to the apprentices in their course book, displayed in the same way on a dedicated TinkerSheet. This formula is rather complicated in comparison with the average math level of most apprentices and the number of parameters involved makes it not very easy to interpret intuitively. The aim of the teachers was thus to let apprentices experiment with the parameters of the formula, allowing them to observe how they influence the optimal reorder size by modifying the curves of costs.

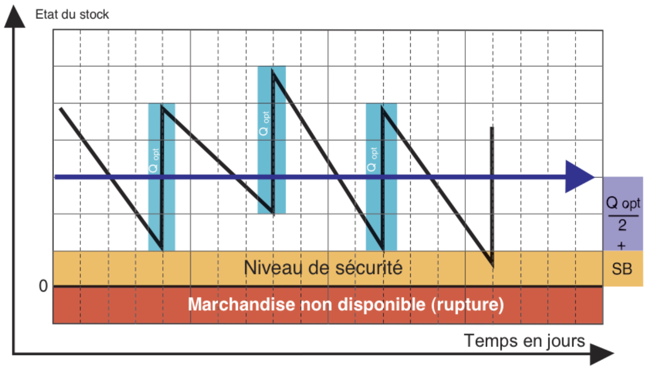


Figure 7.22: Study 8: The Andler formula chart as it is presented in the apprentices' learning material. It represents a trade-off between storage costs which increase with higher reorder sizes (blue curve) and orders fixed costs which decrease with higher reorder sizes (green curve). The intersection of these two curves defines the optimal reorder size.

Lesson plan The lesson plan relies on an exploratory learning scenario: apprentices were given some freedom to discover the effects of different parameters on storage levels (Figure 7.23). At the beginning of the session, apprentices were instructed to build a warehouse layout that would then be used during the rest of the activity. This part was optional as previously created layouts can be saved using a dedicated TinkerSheet and reloaded at any time. When the apprentices were satisfied with their design, the teacher froze the layout and asked them to remove all the elements of the small-scale model. The projection of the warehouse was then reduced to 25% of its original size and switched to a 2D mode. The teacher finally set initial external parameters (customer demand, delivery delays and costs) and launched a simulation in fast mode. Three types of products are used during this simulation mode and parameters for each of them can be set independently (e.g. customer demand, reorder strategy, . . .). The central part of the activity was to first equilibrate the reordering parameters to cope with the initial external parameters and then test different external parameters to observe their influence on the storage strategy and the Andler formula.

Available TinkerSheets The apprentices and their teacher used twelve different TinkerSheets during this activity. Each of the three products has two dedicated sheets to control external parameters (i.e. parameters that can not be controlled by logisticians such as customer demand or suppliers' delivery delays) and the reorder strategy. Two other sheets display charts showing storage levels and storage breaks. The curves of all the products are displayed on the same graphs but it is possible to focus on one product only. A sheet was used to display a graphical representation of the Andler formula. The three last sheets were dedicated to the control of the simulation as well as saving and loading functionalities.

Figure 7.23: Study 8: A group of apprentices working on the storage management activity with Simon Lépine (facing the camera), who developed the chart visualizations used in this module as part of his Master thesis.

Use of MERs

The physical flow of items is represented twice: as an animation of the content of the shelf on the projected warehouse layout and by the evolution of the curves on the charts displayed on TinkerSheets. Understanding the meaning of disembodied charts is made possible by the animation of a concrete representation.

Observations

During this session, apprentices were working with abstract representations, using mostly TinkerSheets. What we observed is that they were able to read and make sense of the curves displayed on the charts: they discussed about them and proposed corrective measures when the storage level was not appropriate (e.g. too low because of an augmentation of customers orders). What appeared is that the relationships between reorder limit, reorder size and external parameters were not understood by most of the apprentices because their propositions were usually wrong (e.g. simply augmenting the amount of pallets ordered does not solve the problem when demand is to high, the reorder threshold has to increased as well to receive the goods before a storage break). When asked to react to an increase of the suppliers' delivery time, they often had the wrong reaction and augmented the size of the reorders and were then surprised to see that they ended up having systematic storage breaks. The simulation was useful to illustrate in a dynamic example the impact of external parameters on storage levels and how a logistician can react to avoid storage breaks.

Another interesting observation is that the two-dimensional down-scaled pro-

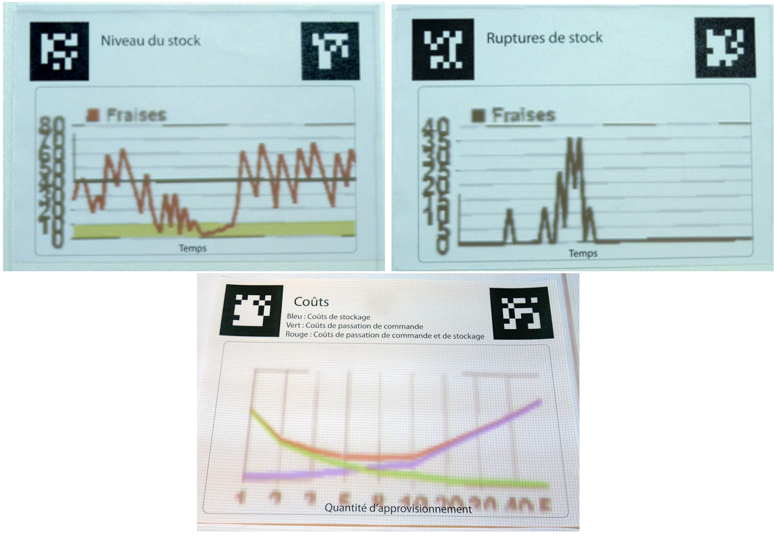


Figure 7.24: Study 8. Top left: TinkerSheet displaying the storage level of three product types on a dynamic chart. Top right: TinkerSheets displaying the storage breaks of three product types. Bottom: Graphical representation of the Andler formula on a TinkerSheet. Reorder size is given on the horizontal axis, costs on the vertical axis. The blue curve (increasing value with the order size) stands for the storage costs and order costs are given by the green curve (decreasing value with the order size). The red curve (U-shape) represents the sum of the storage and the order costs, and its minimum value indicates the optimal theoretical order size.

jection of the warehouse layout was useful to ground the values presented on the TinkerSheets. On several occasions, the teacher asked a group to look at the warehouse when it was showing an almost empty storage area. He discussed with them the pertinence of keeping the warehouse most of the time empty and the different actions that could be taken to reduce the costs (i.e. move to a smaller warehouse or rent available space). This example also illustrates some values that would be necessary to display on TinkerSheets if we wanted to create a representation getting rid of the warehouse layout, like the percentage of available space in the warehouse for instance.

7.3.4 Discussion of Phase 3 studies

The three studies reported in this phase illustrated the use of the Tinker Environment at different stages of the apprenticeship of logisticians. The first general comment we can make about these observations is that the pedagogical model we implemented seems to be adequate. The level of representation offered at each stage seems to be well adapted. The apprentices are able to *read* the different representations, which allowed them to actively engage in the activities. The difficulties encountered by several groups in the first activity show that they really need a representation at least as concrete as the small-scale model. Most of the problems identified during the activities come less from the level of representations than from a lack of comprehension of the concepts: apprentices were able to use the representations to engage in the activity and propose solutions, but the solutions proposed were often wrong because of a misunderstanding of the underlying concept (e.g. reactions to storage breaks with an incorrect measure). In these cases, the environment allowed the teachers to identify the concepts that were not clear for apprentices and focus on them during the activity. These examples also demonstrate the importance of the collaborative setting offered by the TinkerTable. A pattern we often found in the groups we observed is that some apprentices had a better understanding of the concepts addressed during the activity and explained them to their peers.

These three situations give an overview of the progressive move towards abstract representations and the use of MERs at each level. During the first activity, the main representation is the small-scale model. TinkerSheets are used only for displaying information that is embedded in the model itself. The number of shelves, for instance, could be obtained by simply counting them. The same is true for the amount of available storage places. We can not really use the term MERs here, but our assumption is that we still have multiple representations embedded in the small-scale model. As described earlier, the small-scale model offers a strong link with both the virtual world and the workplace of each apprentice. Each object thus represents two things in the mind of apprentices: the interface to the simulation and an authentic workplace. We lack however clear evidence showing that these two internal representations really coexist in apprentices' mind.

During the second activity, the focus is both on the small-scale model and on the TinkerSheets. The action is mainly taking place on the small-scale model, as apprentices have to move the shelves to optimize surface usage. Little action happens on the sheets, but they display the most interesting information. They show the score that is used to optimize the layout: the values of the different kinds of surfaces. Three external representations are available for apprentices. The placement of shelves on the table, which could allow them to estimate their score, the graphical representation of the warehouse layout on a TinkerSheet and the textual representation of the actual surfaces values. The goal here is to relate the abstract information of a percentage of net storage value to a visual representation. Our hope is that apprentices will get an intuitive understanding of what it means to have a percentage of net storage surface of 23%. Is it a lot? How does a warehouse with such a percentage looks like?

In the last activity reported, the focus is mainly on the TinkerSheets, both in terms of actions and information seeking. The information displayed on the TinkerSheets is made of charts showing the evolution of storage levels and storage breaks. The small-scale model has been removed from the table and is now projected in a down-scaled 2D way, reduced to a role of awareness information. Our observations show that this representation is still important as it links the abstract information displayed on the charts to its meaning in an actual warehouse layout. It allowed the teacher to point out some problems that would have gone undetected on the sheets.

Open issues The main issue concerned the lack of time dedicated to reflection during the activities involving the use of the system. Apprentices effectively

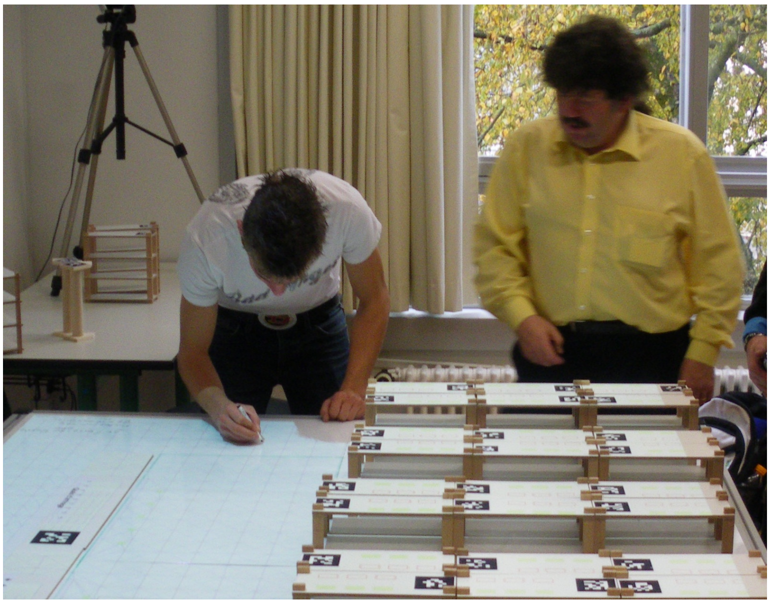


Figure 7.25: An apprentice writing down results on the whiteboard surface of the TinkerTable.

switched between different levels of representations during a particular session, but the lack of planning and self-regulation already observed during the Phase 1 studies was still present. This problem has been confirmed with semi-controlled experiments conducted during sessions similar to the three examples reported above, where pre- and post-tests were distributed to groups working in the same class with either the Tinker Environment or pencil-and-paper exercises. Results did not show any significant difference between these two conditions. The performance at the post-test was usually surprisingly low, even if it assessed relatively simple concepts such as the types of surfaces used to describe a warehouse. We do not report these results in details here but limit the discussion to the relevant qualitative observations that might explain the absence of difference among the two conditions. The bad results can be partly explained by the fact that apprentices did not take these tests seriously (we actually heard some comments which confirmed this impression). This lack of engagement in the test is not enough to explain the poor performance we observed: the main problem probably comes from the lack of reflection during the activity. Understanding the link between two representations at different levels of abstraction is a good step but does not mean that the underlying concept is really mastered and can be reused afterwards. The intuitive discoveries and observations made during the interaction with the Tinker Environment should ideally be anchored through debriefing sessions, where the solutions found by different groups would be compared and discussed with the teacher.

We expected that the teachers would take advantage of the possibility to write results directly on the TinkerSheets as a way to take some data out of the Tinker

Environment and bring it back to the classroom for a debriefing session. This did not happen: teachers asked apprentices to write down results for this purpose but on the whiteboard surface of the TinkerTable (Figure 7.25) or on a piece of paper for groups working with the TinkerLamp. Several reasons may explain this behavior. First, teachers probably gave a higher value to the TinkerSheets than to standard sheets of paper because of their particular usage. They also had a limited number of them and wanted to be sure that they would have enough for each group. Second, and probably most importantly, the organization of interface elements on the sheets was not designed with this purpose in mind and was thus not adapted to the reuse of results written down on them in the classroom. The teachers nonetheless organized short debriefing sessions: they asked apprentices to copy the results obtained with the simulation on the blackboard and use them to make some concluding remarks. In practice, the time left for these debriefing sessions was short and apprentices often did not give it much attention.

Another problem identified during these DBR studies is the difficulty for teachers to manage several groups. What we observed is that apprentices are strongly dependent on the teacher during an activity. They tend to be quickly satisfied with a solution and do not try different approaches by themselves. As a result, much time was spent waiting for the teacher to come back to the group.

7.4 Phase 4: Integrating the Tinker Environment in the classroom

The previous phases have uncovered a range of open issues in the use of the Tinker Environment in classrooms. From a pedagogical perspective, our observations have shown a lack of reflection among apprentices during activities with the system. The management of the activities also proved to be difficult for the teachers, since apprentices depend on them to get instructions. Good debriefing sessions, which have the potential to bring apprentices to reflect on their activity, were also usually missing. From a usability point of view, our observations showed that there was some room for improvement in the integration of TinkerSheets in the environment since they compete for space with the small-scale model. These issues are addressed in the two studies reported in this last phase.

We first describe a semi-controlled experiment that aimed to increase the level of reflection of apprentices during an activity with the Tinker Environment and facilitate the management of the class by the teachers, thanks to written instructions distributed to apprentices. We improved the usability of TinkerSheets in two ways. We placed four of them on A4 sheets of paper and reduced the size of the warehouse to leave some space for the sheets. Results were unfortunately disappointing.

We then report observations from a DBR study of activities involving the use of a new type of TinkerSheets created after the negative results of Study 9: Integrated TinkerSheets. These sheets did not imply any technological change to the Tinker Environment, but their format and design has been adapted to better support both teachers and apprentices.

	Class 1	Class 2
Morning	Tangible Paper	Paper Tangible
Afternoon	Paper Tangible	Tangible Paper

Table 7.5: Study 9: Original planning of the study for each class.

7.4.1 Study 9: structured activity

This study is a semi-controlled experiment conducted during two full days with four different classes at the CPNV. It took place during official school days towards the end of the year and was presented to the apprentices as an annual revision, covering the most important topics of the two first years of the apprenticeship. We organized the activity as a full-day scenario, placing the apprentices in the role of the director of a company building a new warehouse and defining the storage management strategy. The objective was to assess the impact of several modifications we made to improve the organization of activities with the Tinker Environment. The improvements concerned the management of the activities by the teachers and the support for reflection among groups of apprentices.

In order to facilitate the task of the teachers, written instructions were distributed to each group. The objective was to give some independence to the apprentices in the achievement of the task, such that they do not have to wait anymore for the teacher to tell them what to do next. One of the reasons why groups spent a lot of time waiting for the teacher also came from the fact that they are quickly satisfied with a solution and do not explore different approaches. This issue was also addressed in the instructions by explicitly telling apprentices to test several options and guiding them in this task. Reflection was encouraged in a similar way, with questions concluding each phase of the activity and asking groups to comment their results and/or observations.

The results were written down directly in the instructions, but also on TinkerSheets which were grouped on A4 sheets to facilitate the handling of the activity documents. Usability issues related to the competition for interactive space between TinkerSheets and the warehouse small-scale model were addressed by reducing the surface of the warehouse to leave free space on the side for the sheets.

Method

Participants The study involved four classes over two days (two times two classes during a full day), with a total of 60 apprentices in their second year of apprenticeship. Each class was familiar with the Tinker Environment because it had been used several times during the year.

Procedure: overview The day started with a common briefing session involving the two parallel classes taking part to the study and their teacher. Each teacher was

	Class 1	Class 2
Morning	Tangible	Paper
Afternoon	Paper	Tangible

Table 7.6: Study 9: Planning of the study for each class after removing some originally planned parts because of time constraints.

Figure 7.26: Study 9: Classroom layout in the tangible condition. Four TinkerLamps are placed in a cross-like shape.

assigned to a given condition: the same teacher was responsible for the tangible condition during the two days of the study, while two different teachers were involved in the paper condition. The goal of this initial briefing was to explain the plan of this particular school day to the apprentices. Each class was then instructed to join its classroom to start the activity.

The study was divided in two main phases, addressing different topics: the morning phase was dedicated to warehouse layout problems and related concepts such as surfaces and types of forklifts while the afternoon phase focused on storage management issues. Each phase was further divided in two parts including similar activities but performed in the two conditions by each class. We followed a crossed within-subject design, summarized in Table 7.5. This initial planning had to be abandoned during the study because the time needed by groups to perform the task was much higher than expected. Each phase was thus reduced to a single part, as shown in Table 7.6.

Each phase followed a similar structure. The apprentices were first divided in

Figure 7.27: Study 9: Teacher giving instructions to a group of apprentices in the paper condition.

groups of three to four and assigned a place in the room. In the tangible condition, four TinkerLamps were installed in the center of the class in a cross-like shape (Figure 7.26). The groups in the paper condition sat in each corner of the room around two tables. (see Figure 7.27. They were then asked to fill an individual pre-test during 15 minutes. After collecting the tests, the teachers distributed several documents to each group, including instructions and work sheets used to write down results and interact with the TinkerLamp in the tangible condition. Each work sheet was composed of four TinkerSheets printed on an A4 paper sheet. The reason why TinkerSheets were given to the groups in the paper condition was because they were supposed to be reused in the second part of the activity which, as already stated, was cancelled because of time constraints. The apprentices were then asked to follow the instructions and were free to organize their work. Teachers stayed in the room and were available for questions. The duration of each phase was about three hours. At the end of the morning phase, a post-test was given to apprentices to assess their knowledge and understanding of the material addressed during the session. Two post-tests were distributed at the end of the afternoon phase, testing apprentices' knowledge and understanding of the concepts addressed during the session and a delayed post-test focused on the morning phase material. The apprentices were then free to leave the room and went to lunch (morning phase) or home (afternoon phase).

Procedure: Morning phase The written instructions distributed to each group presented the scenario of the day. The context was the following:

You are the directors of a company which sales beverages. You bought warehouse A five years ago from a company which went into bankruptcy. The business went well during the previous years and you now have enough money to expand it. You decided to build a new warehouse, better adapted to your needs. A specialized architect proposed warehouse B, and you would like to assess its quality, compare it to your current warehouse and modify it to make it as profitable and efficient as possible.

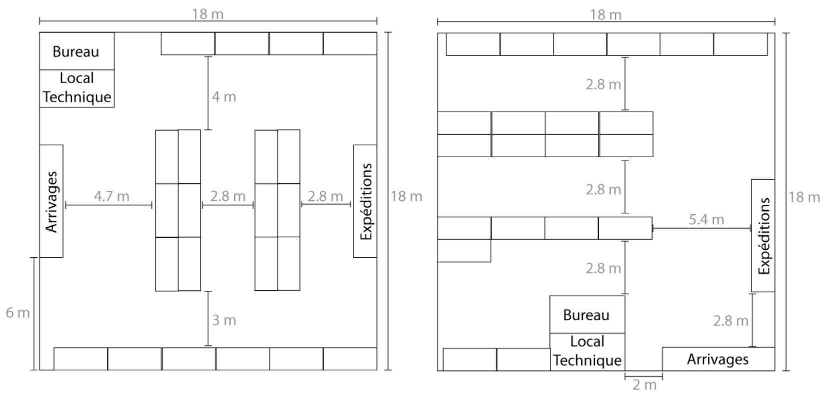


Figure 7.28: Study 9: Blueprints of warehouses A (left) and B (right) used during the morning phase.

The blueprints of warehouses A and B were distributed on additional sheets (Figure 7.28). The work sheet used during this phase is shown on Figure 7.29. It displays the blueprint of the warehouse, provides information about surfaces and storage capacity. It also gives access to simulation controls and corresponding data (e.g. number of pallets expedited). Apprentices were then instructed to perform a series of tasks, described below. If not stated otherwise, the instructions were the same for the paper and the tangible conditions.

1. *Evaluation of Warehouse A.* Apprentices first had to look at the warehouse blueprint, discuss it with their peers and write down their observations. Some hints were provided in the form of questions asking if the warehouse seemed well organized, if the work would be efficient as well as its positive and negative aspects.

   Groups in the tangible condition then had to implement the warehouse with the Tinker Environment small-scale model, after placing the working sheet below the lamp to load the corresponding parameters. When this was done, they were instructed to write down the information projected by the system about the warehouse surfaces on the work sheet. They also had to read the surfaces' definition reminder written on the sheet and answer a question. The same had to be done for the distances from delivery and expedition docks to each shelf, but apprentices were asked to estimate these values before reading

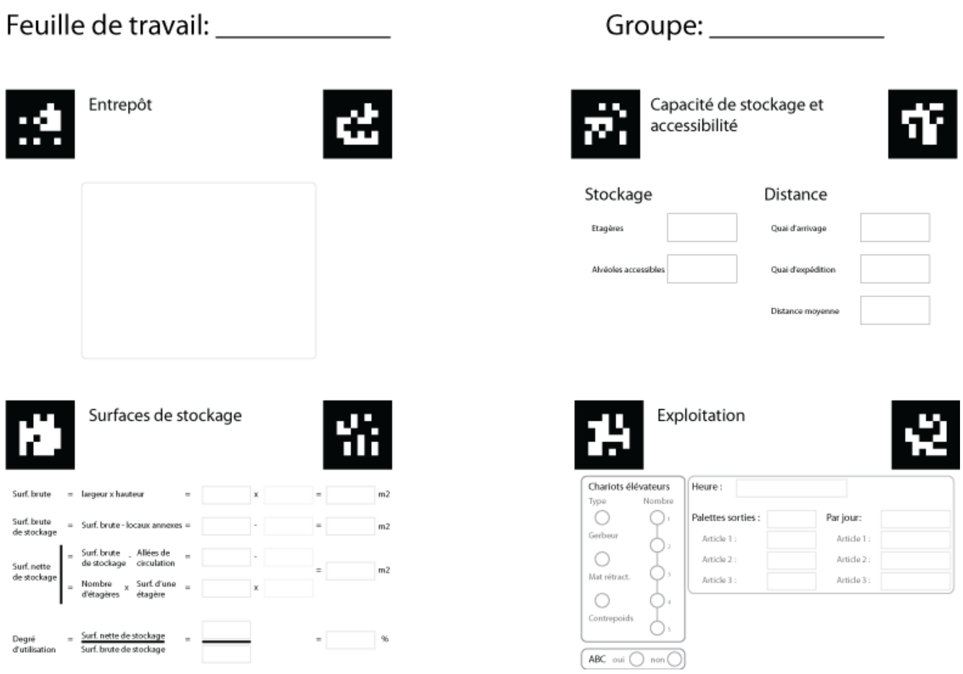


Figure 7.29: Study 9: Work sheet used during phase 1. It includes four TinkerSheets that display the warehouse blueprint (top left), information about surfaces (bottom left) and storage capacity (top right). The sheet located at the bottom right gives access to simulation parameters (type of forklifts, ABC analysis), controls (start/pause) and associated information (e.g. number of pallets moved to expedition).

them and explain their estimation strategy. They finally ran a simulation which simulated the expedition of 100 pallets and wrote down the results displayed on the work sheet, including the number of pallets delivered and a daily extrapolation.

In the paper condition, the structure of the activity was the same but no implementation was done since the warehouse small-scale model was not available and results obtained from the simulation in the tangible condition had to be computed by hand (e.g. surfaces) or estimated when no exact value can be found (e.g. average distance between docks and shelves, or number of deliveries per day).

2. *Evaluation of Warehouse B.* This part was the same as the previous, but for Warehouse B.

3. *Comparison.* The apprentices then had to compare the warehouses A and B. This was done by filling a table which asked them to describe, for each warehouse, its positive and negative points, the type of products for which the layout is adapted and potential improvements.

4. *Improvement.* In this part, apprentices were instructed to improve warehouse

B. In the tangible condition, the modifications were done directly on the small-scale model, using the values displayed on the work sheet as a way to evaluate the quality of the solution. When these groups were satisfied with their solution they had to write them down on a new work sheet and explain the improvements they brought to the layout. They finally tested this new layout with a simulation. In the paper condition, the same task had to be performed but without the small-scale model nor the simulation. Apprentices had to draw their solution on the work sheet directly and provide explanations as well.

5. *Forklift type.* The next task concerned the choice of the forklift type to use in the warehouse. Three models were proposed which differed in terms of size and speed. Apprentices first had to check which type could be used in their warehouse (some might be too large for the alleys' width in their layout). They then had to compute how many workers should to be hired to perform a given amount of deliveries per day. An estimated time of 1.5 minutes per pallet was given to apprentices in the paper condition. The time obtained during the simulation run during the last part was used in the tangible condition.

6. *ABC analysis.* For this last part, groups in the tangible condition were instructed to run a simulation without using an ABC analysis for the placement of goods in the warehouse and compare it to the results obtained during the previous simulations (which used this analysis). In the paper condition the task assigned to apprentices was to manually compute an ABC analysis based on given amounts of customer orders for the three types of products stored in the warehouse.

Procedure: Afternoon phase After working on the warehouse layout and the organization of the goods during the morning phase, the scenario continued in the afternoon with storage management tasks. The context given to the apprentices was:

> *Your business goes well. You distribute beverages in each part of Switzerland but notice that a centralized warehouse is not the optimal solution. You thus decided to open 20 local warehouses. Since you are satisfied with the layout and organization of your current warehouse, you keep it for your regional warehouses. You now have to think about the storage management issues for these new warehouses. You want to evaluate different strategies for each product and choose the one that best corresponds to your needs.*

The worksheet used during this phase is shown on Figure 7.30. The instructions given to each group are listed below.

1. *Layout.* Groups in the tangible condition were first asked to reproduce the warehouse layout drawn during the morning with the small-scale model. This warehouse was then saved and displayed by the system at a smaller scale, to be used for a faster-paced simulation as described in Section 6.5.3.

2. *Optimal order quantity.* The goal of this part was to compute an optimal order quantity for each of the three product types using the Andler formula

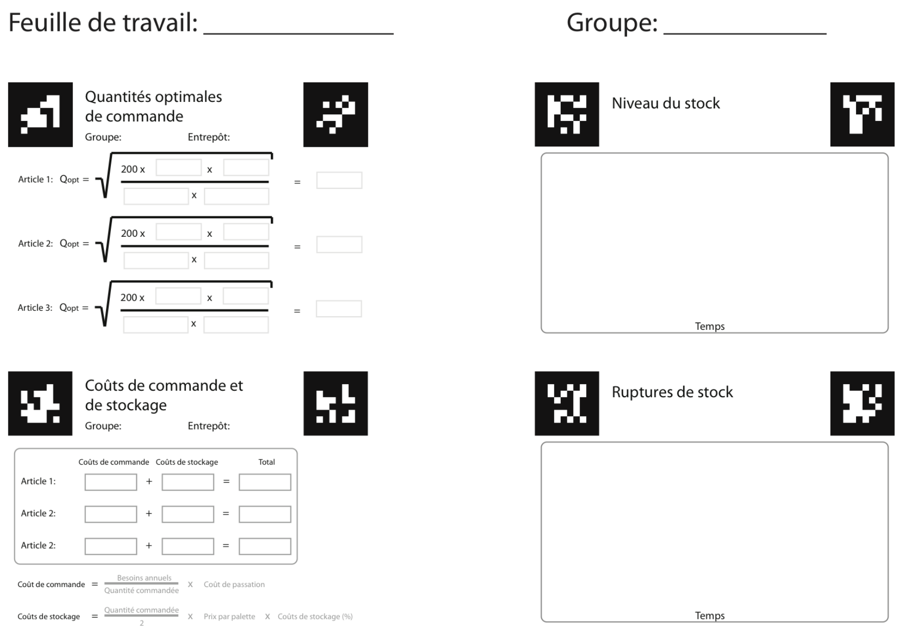


Figure 7.30: Study 9: Work sheet used during phase 2. It includes four TinkerSheets that display the Andler formula for each product type (top left), storage and reorder costs (bottom left). The two sheets on the right display storage level (top) and storage breaks (bottom) charts.

(see Section 5.1.2). Expected customer order rates as well as other relevant information about each product was given on a separate information sheet. In the tangible condition, the actual computation was done by the system. Apprentices had to input the right parameter on the work sheet and they would be automatically introduced in the formula. They were instructed to check the correctness of the result and write it down. In the paper condition, apprentices had to compute this result manually, using the work sheet to write the parameters in the given formula mask.

3. *Reorder point.* In this part, apprentices had to define the reorder point for each product (i.e. the storage level at which an order is issued to the supplier). A reminder of the formula used to compute this value was given in the instructions and groups had to compute it manually in both conditions.

4. *Costs.* The objective of this part was to understand the impact of the order quantity and the annual customer demand on the costs (storage and order). Groups were asked to answer specific questions (e.g. what happens if the customer demand is multiplied by two?) but also to explore by themselves the implications of different combinations of parameters' values. The Tinker Environment allowed apprentices in the tangible condition to explore these aspects by changing parameters on the work sheet and get an immediate result. Apprentices in the paper condition did the same but had to compute

the changes manually.

5. *Simulation.* This last part aimed at exploring the impact of different parameters on the storage levels and the risk of storage breaks and to learn which corrective measures have to be taken in those situations. Three parameters were considered: customers' annual needs, suppliers' delivery delays and customers' daily needs. In the tangible condition, apprentices were instructed to run a simulation and observe the impact of the modification of each parameter, one after the other, on the storage level and explain what they observed. In the paper condition, apprentices had to imagine what this impact would be and draw a storage level chart to illustrate their conclusions.

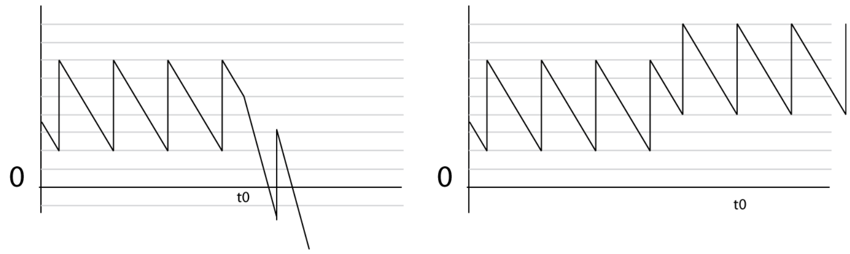


Figure 7.31: Study 9: Examples of storage level charts that apprentices had to interpret during the pre- and post-tests of the afternoon phase. Left: customer demand for this product has increased, no corrective measure has been taken and there is thus a storage break. Right: the reorder point has been increased by the storage manager, the average storage level is now higher.

Material Four TinkerLamps were used in the tangible condition. Each group in both conditions was recorded by a camera, placed on top of the lamp in the tangible condition and on a tripod next to the group in the paper condition, and a microphone placed on the table.

Several paper documents were used: two sets of instructions (one for the morning phase, one for the afternoon phase) adapted to each condition, information sheets providing additional data related to the types of products stored in the warehouses and the type of forklifts available, and work sheets for each phase.

Measures Ad-hoc pre- and post-tests were designed to measure learning gain. Each test followed a similar structure made of two parts adapted to the topic covered by each phase. The first part (2 to 3 questions) included declarative knowledge questions to test the apprentices' knowledge of the theoretical concepts, such as *"What is the definition of the net storage surface?"*. The second part (4 to 5 questions) included inference questions that assessed the capacity of apprentices to apply this knowledge to *what if* scenarios, like for example *"if you augment the alley width of a warehouse, what happens for the raw surface/the number of shelves/the space available for moving?"*. In the morning phase, apprentices had to compare two warehouses' layouts and propose improvements for one of them. In the afternoon

	Paper			Tangible		
	Pre-test	Post-test	Gain	Pre-test	Post-test	Gain
	Morning					
Global	46.8	48.9	**2.1**	47.5	44.9	**-2.6**
	(17.1)	*(19.8)*	*(21.4)*	*(16.5)*	*(18.8)*	*(14.9)*
Declarative	17.2	40.5	**23.3**	15.8	25.8	**10.0**
knowledge	*(26.0)*	*(32.3)*	*(38.3)*	*(26.7)*	*(32.5)*	*(33.9)*
Inference	58.6	53.1	**-5.5**	60.2	54.5	**-5.7**
	(19.1)	*(16.3)*	*(20.1)*	*(18.9)*	*(17.8)*	*(15.5)*
	Afternoon					
Global	54.0	58.0	**3.3**	57.5	53.9	**-1.8**
	(18.8)	*(17.4)*	*(15.0)*	*(14.8)*	*(17.5)*	*(14.1)*
Declarative	62.1	65.8	**1.5**	63.3	61.1	**<.001**
knowledge	*(29.5)*	*(25.5)*	*(23.8)*	*(21.2)*	*(21.8)*	*(25.5)*
Inference	49.1	53.3	**4.4**	54.0	51.6	**-2.4**
	(20.1)	*(19.1)*	*(17.9)*	*(18.5)*	*(19.0)*	*(18.8)*

Table 7.7: Study 9: Means and (standard deviation) of scores obtained at the pre-test, the post-test and the gain for each condition. Three scores are reported: global, declarative knowledge questions and inference questions.

phase, apprentices had to find which kind of event explains a break of regularity on a storage level chart (see Figure 7.31). Each item was evaluated on the following scale: 0 (wrong), 1 (partially correct) and 2 (correct answer). The global score was computed as the percentage of points obtained in the test compared to the maximum possible points. The score for declarative knowledge and inference questions was computed as the percentage of points obtained in the corresponding subset of questions. The learning gain was computed for each participant by subtracting the pre-test score from the post-test score.

Results

Quantitative analysis The scores obtained by the participants to the pre- and post-tests during the morning and afternoon phases are shown in Table 7.7. Global scores do not show any significant difference between the tangible and the paper condition in either phase. The same is true when declarative knowledge and inference questions are considered independently.

The interesting although somewhat disappointing observation that can be made from these results is that apprentices did not learn. Even though the scores in the pre-tests leave room for improvement (global scores at pre-tests range between 40% and 60%), gains are surprisingly low (maximum 3.3% in the paper condition of the afternoon phase) and sometimes even negative. The only values above 5% concern declarative questions during the morning phase, with a gain of 23% for the paper condition and 10% for the tangible condition. The difference between these two values is the highest among the two conditions but is not significant, $t(57)=1.41$,

p=.16.

Observations The observations conducted during this study show that the format adopted for the activity was not adapted. The relative independence given to the groups by the written instructions had a negative impact on the apprentices' motivation and engagement in the task. Much time was spent talking about unrelated topics rather than working on the task. These observations were confirmed by the material handed in by the apprentices at the end of the activity: three of the four classes that took part to the study completed in average only one half of the expected tasks. This is particularly surprising since the time allocated had already been doubled compared to the initial plan. The last class managed to do all the assigned tasks, and can be explained by a teacher effect. Indeed, the teacher responsible for this class (paper condition) carefully checked that each grouped gave an answer to each part of the instructions. The questions aimed at encouraging reflection during the activity did not play their role: apprentices usually gave short answers that were not actively discussed within the group.

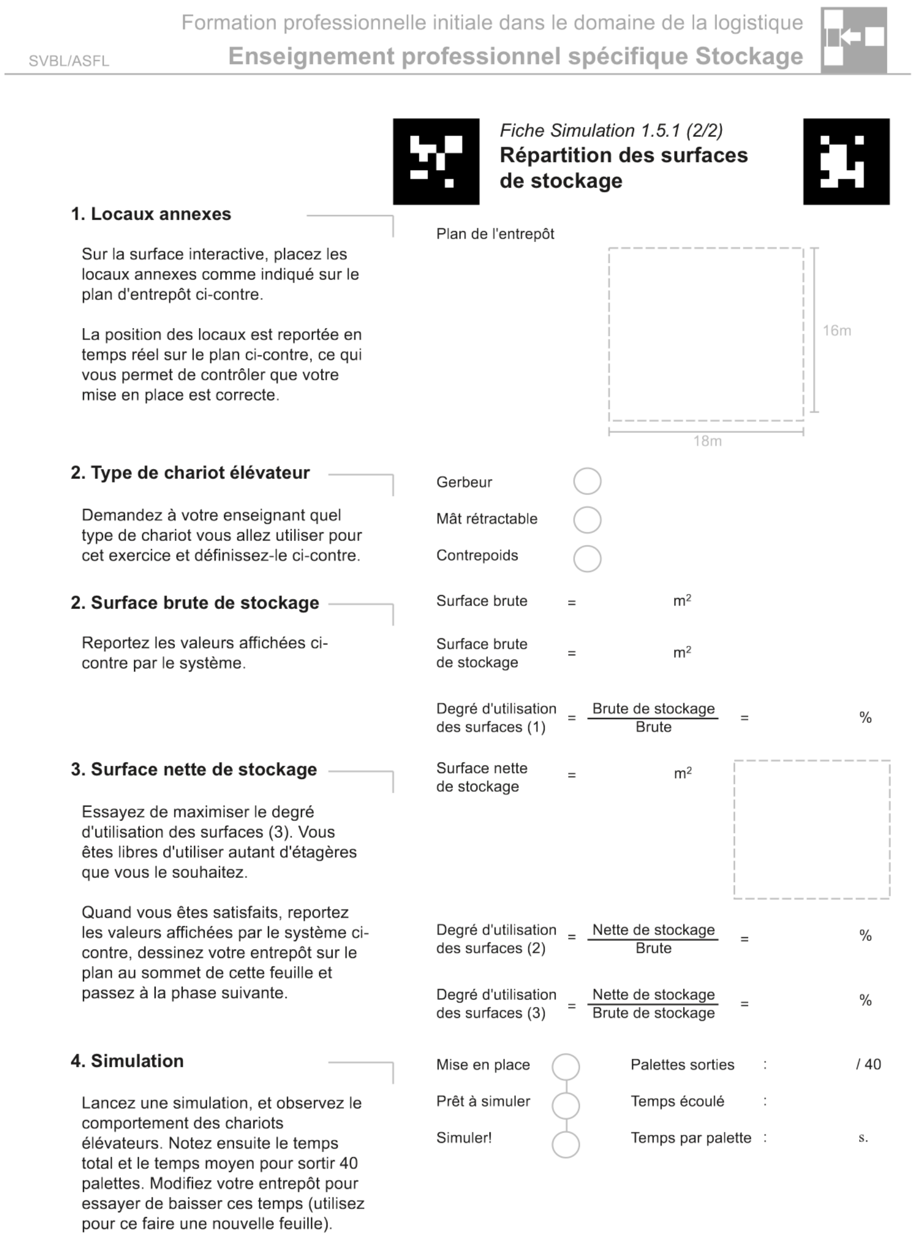
The teachers took an unexpected role during the activity, spending most of the time observing apprentices and answering questions whenever necessary. While we told them beforehand that they were encouraged to teach at their convenience, they seemed to rely on the written instructions to guide the apprentices through the activity. The fact that we were distributing pre- and post-tests probably partly explains this behavior since they did not want to influence the results.

7.4.2 Study 10: integrated TinkerSheets

This DBR study covers observations gathered during four two-hour sessions involving two different activities (two sessions each). These activities were designed during the summer following the observations described in the previous study and aimed at overcoming the issues that we identified. In particular, we observed that providing apprentices with detailed written instructions did not allow them to engage in the activity and did not help the teachers to manage the class.

A new approach was tested during this study, based on simplified activities and two types of documents: a written description of the lesson plan for the teacher, explaining the organization of the activity and the main steps with an estimated completion time, and a new type of sheets called *Integrated TinkerSheets* (see Figure 7.32). The main differences compared to the initial TinkerSheets are the format (A4), which is better adapted to their storage with other documents, and the organization of printed content in two columns. The left column is dedicated to a description of the task, reminders of theory and/or definitions; the right column contains the interface elements, arranged in a sequential way reflecting their use in the activity. Compared to the initial design, Integrated TinkerSheets are specifically targeted to a given activity which plan is reflected in the spatial organization of their content. They are thus comparable to an exercise sheet. The detailed lesson plan was prepared in advanced in collaboration with the teacher.

Since self-regulation appeared to be an issue in the groups we observed during the previous studies, the new activities put a strong focus on teacher guidance and



Formation professionnelle initiale dans le domaine de la logistique

SVBL/ASFL **Enseignement professionnel spécifique Stockage**

Fiche Simulation 1.5.1 (2/2)

Répartition des surfaces de stockage

1. Locaux annexes

Sur la surface interactive, placez les locaux annexes comme indiqué sur le plan d'entrepôt ci-contre.

La position des locaux est reportée en temps réel sur le plan ci-contre, ce qui vous permet de contrôler que votre mise en place est correcte.

Plan de l'entrepôt

16m

18m

2. Type de chariot élévateur

Demandez à votre enseignant quel type de chariot vous allez utiliser pour cet exercice et définissez-le ci-contre.

Gerbeur

Mât rétractable

Contrepoids

2. Surface brute de stockage

Reportez les valeurs affichées ci-contre par le système.

Surface brute = m²

Surface brute de stockage = m²

Degré d'utilisation des surfaces (1) = Brute de stockage / Brute = %

3. Surface nette de stockage

Essayez de maximiser le degré d'utilisation des surfaces (3). Vous êtes libres d'utiliser autant d'étagères que vous le souhaitez.

Quand vous êtes satisfaits, reportez les valeurs affichées par le système ci-contre, dessinez votre entrepôt sur le plan au sommet de cette feuille et passez à la phase suivante.

Surface nette de stockage = m²

Degré d'utilisation des surfaces (2) = Nette de stockage / Brute = %

Degré d'utilisation des surfaces (3) = Nette de stockage / Brute de stockage = %

4. Simulation

Lancez une simulation, et observez le comportement des chariots élévateurs. Notez ensuite le temps total et le temps moyen pour sortir 40 palettes. Modifiez votre entrepôt pour essayer de baisser ces temps (utilisez pour ce faire une nouvelle feuille).

Mise en place — Palettes sorties : / 40

Prêt à simuler — Temps écoulé :

Simuler! — Temps par palette : s.

Figure 7.32: An Integrated TinkerSheet. The left column contains a description of the activity as well as theory reminders and definitions. The left part is dedicated to interface elements.

class discussions. Activities include cycles between independent group work with the Tinker Environment and results sharing and discussion with the rest of the class.

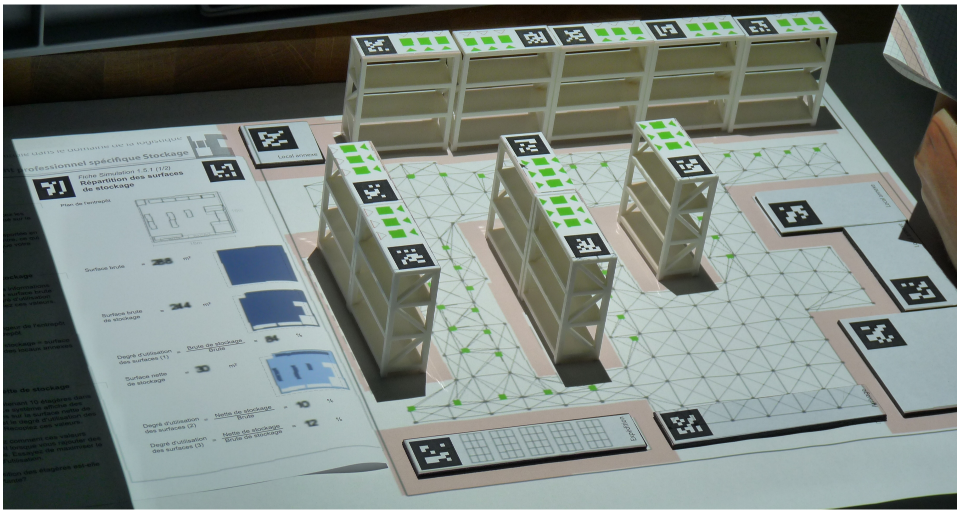


Figure 7.33: Study 10: An integrated TinkerSheet next to the warehouse small-scale model during the surface activity.

Description

The two activities that we observed during this study are a modified version of the *surface activity*, already encountered several times in the previous phases, and a new *levers activity* based on the center of gravity and levers' law modules introduced in Section 6.5.4. The objective of this later activity is to teach important security-related concepts based on the application of the center of gravity and the levers' law to the moving of goods with forklifts in a warehouse.

The *surface activity* is implemented on two Integrated TinkerSheets, used in combination with the warehouse small-scale model. The first is only composed of feedback zones, displaying the different types of surfaces of a warehouse both in graphical and numerical forms (Figure 7.33). The second sheet (shown on Figure 7.32) lets apprentices select the type of forklifts to be use in the warehouse, provides some information regarding the net storage surface (which is the only one important at this stage of the activity), contains buttons to control the simulation and displays associated feedbacks.

The *levers activity* includes four Integrated TinkerSheets. Two of them are dedicated to the gravity-center part: one for input, made of three large pallets where apprentices can place small tokens representing content, and one for the feedback, which shows for each box its content and the resulting position of the gravity center. The levers law part is made of two sheets with a similar content made of three levers and space where the position and weight of pallets on each lever is displayed. When a sheet is placed under the TinkerLamp, the system displays three levers on which wooden pallets can be placed. These pallets have different weights which make the lever move according to the levers law. The difference between the two TinkerSheets is in the number of weights allowed on each lever: two for the simplified law and three for the general law. Another difference is that the position of two pallets is fixed on the third lever of the second sheet. Moreover, a forklift is displayed by the system on top of this lever when it is equilibrated, to illustrate the fact that a forklift loaded with a box can be seen as a lever with three loads: if the box is too heavy the forklift falls and may hurt the driver.

Figure 7.34: Study 10: An apprentice copying a warehouse layout on an Integrated TinkerSheet.

Lesson plan

The two activities follow a common structure. The first part is dedicated to an introduction by the teacher who explains the context and gives some basic information about the theoretical concepts that will be addressed during the activity. Groups of 3 to 4 apprentices are then formed and assigned to a TinkerLamp where they receive the corresponding Integrated TinkerSheets. Each step of the activity is then read and commented by the teacher with the apprentices before the groups engage in an independent work. The results are written directly on the Integrated TinkerSheets and shortly discussed with the rest of the class before working on the next step. The last part of the activity is dedicated to a debriefing session: a member of each group copies the results obtained during the activity on the blackboard and the teacher compares and discusses them with the apprentices.

The *surfaces activity* is composed of five steps:

1. *Raw storage surface.* The apprentices first place expedition and delivery docks and some administrative rooms as indicated on the TinkerSheet. The system displays in real-time the resulting raw storage surface, which is written down by the groups and commented by the teacher.
2. *Net storage surface.* The apprentices are instructed to place ten shelves in the warehouse. They write down the net storage surface displayed by the system. The teacher asks the groups to share the values obtained and discuss them with the class. The objective is to get them to propose solutions to augment the net storage surface, such as reducing the size of the warehouse or adding more shelves.
3. *Optimization.* The groups are assigned different types of forklifts and then have to put as many shelves as possible in their warehouse. The resulting layout is written down on the TinkerSheet together with the information about surfaces displayed by the system.
4. *Discussion on layouts.* Representatives of each group come to the blackboard and copy their layout and corresponding surfaces' values (Figure 7.35). This gives an overview of the solutions produced by the groups and is used by the teacher to compare them and discuss the differences with the apprentices. At the end of the discussion, the teacher asks apprentices to estimate the relative efficiency of each warehouse, tested in the last step.
5. *Discussion on efficiency.* Each group runs a simulation to get an estimation of the time needed to deliver a given number of pallets for each warehouse. These values are reported on the blackboard as well and discussed by the class.

The plan of the *levers activity* is the following:

1. *Gravity center.* The groups are instructed to arrange several tokens in different configurations in the three available pallets and write down the information displayed on the TinkerSheet. The teacher then starts a discussion on the impact of the gravity center on the job of a forklift driver. The objective is to get the apprentices to understand why a box has to be moved from its heavier side.
2. *Levers examples (2 pallets).* Apprentices have to generate three examples of an equilibrated lever, using only two pallets of possibly different weights. The information displayed by the system on the TinkerSheet is written down (Figure 7.36).
3. *Simplified Levers Law.* The teacher takes several examples from different groups and writes them on the blackboard. A discussion takes place to get the apprentices to establish the simplified levers law (2 pallets).
4. *Levers examples (3 pallets).* New examples are generated, using this time three pallets.
5. *Levers law (general).* As for the simplified law, the teacher writes down several examples from the groups on the blackboard and helps the class to discover the general levers law. The importance of this law for the security of forklift

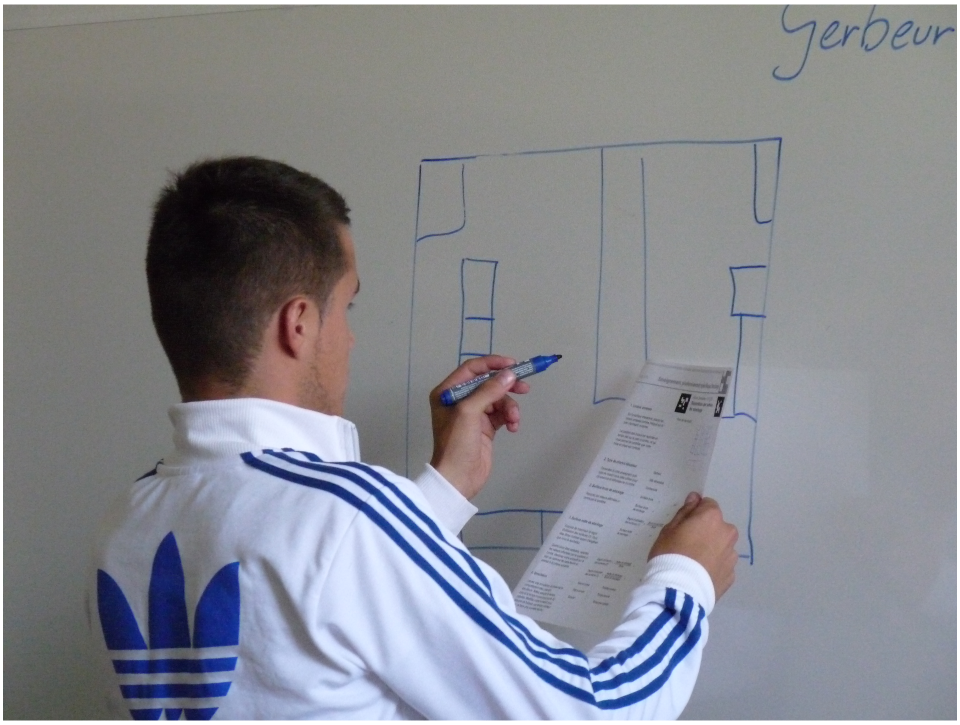


Figure 7.35: Study 10: An apprentice copying results obtained in the Tinker Environment on the classroom whiteboard.

drivers is finally discussed, supported by the forklift displayed by the system when the third lever reaches equilibrium.

Observations

The new approach for the organization of activities around the Tinker Environment had a positive impact on the sessions we observed. Two main factors explain these improvement: on one hand, the scenarios based on Integrated Tinkersheets simplify the activity, support annotations by apprentices which in turn facilitate the setup of debriefing sessions; on the other hand, the teacher took a more active role than during the previous study with a better presence during the activity, with constant explanations, encouragements and management of the whole class. Each step of the activity was introduced by the teacher who ensured that each group was done with it before moving to the next one. The result was a stronger cohesion in the class because all the groups went through the activity at the same pace. The teacher took advantage of this situation, asking for examples groups to have a look to the approach taken by others during the layout step of the surface activity. Compared to the previous study where most of the groups did not manage to complete the tasks assigned to them, the teacher could ensure that the time allocated for the session was respected.

At the group level, we observed that the apprentices appeared to be more engaged

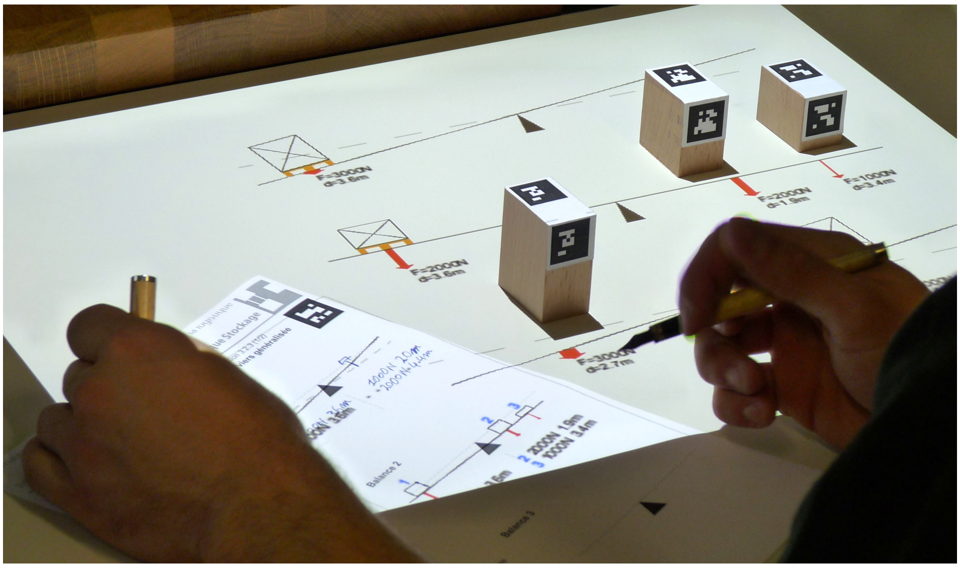


Figure 7.36: Study 10: An apprentice writing down data on an Integrated TinkerSheet during the levers activity.

in the activity than in previous occasions. The stronger presence of the teacher was well accepted and the discussions among the peers were usually focused on the task. The teacher managed to keep a good balance between communications to the whole class for general-purpose comments and suggestions and individual interactions with groups, who thus felt more motivated to improve their solution since they could show it on a regular basis to the teacher to get feedback. The Integrated TinkerSheets also played a role in keeping the apprentices focused on the task. Since available interface elements on each sheet are limited to the inputs and feedbacks necessary for the activity, we did not observe groups randomly changing parameters or running simulations. The shorter text situated directly next to the interface element also appeared to be easier to manage for apprentices who could quickly refer to it if they forgot what the teacher explained at the beginning of each step.

Compared to the previous sessions where the Tinker Environment was involved, the important part dedicated to class discussions during the activity and the time allocated to debriefing at the end of the session put more responsibilities on the teachers. Some time was thus needed for the teacher to find the right way to guide the apprentices through the discussions and the second session was better for both activities. This evolution is reported for each activity in the more details below.

Surface activity The first time the surface activity was tried out, the teacher did not ask the apprentices to reproduce their warehouse layout on the blackboard, but only the numerical values such as different surfaces and time needed to deliver pallets. This made the debriefing session difficult to organize because the values obtained by the groups did not match the expectation of the teacher. For instance, the groups using a larger forklift were expected to get a lower storage capacity and

Figure 7.37: Study 10: debriefing session during the surfaces activity. The teacher asked apprentices to copy both numerical data and warehouse layouts on the classroom whiteboard.

need less time to deliver a given amount of pallets (wider alleys and faster vehicles). Unfortunately these expectations are only valid if the groups find solutions of a similar quality, which was not the case. Groups with smaller forklifts actually got less storage capacity but were faster than groups with the large forklifts. It was then difficult for the teacher to explain the values obtained by the apprentices. The fact that three types of forklifts were used also made the discussion more complicated since more relationships had to be established between values.

These issues were corrected for the second session. The teacher asked apprentices to copy both the numerical values and the warehouse layout on the blackboard. Only two types of forklifts were used and assigned to four groups of apprentices, which gave two solutions for each type of vehicle. The discussion was this time much richer and easier to manage for the teacher since unexpected values could be explained by relating them to the corresponding layout (Figure 7.37). Having several solutions for each type of forklift also augments the chances to get nearly optimal solutions, but they are no longer needed since the information available allows the class to make sense of any result.

Levers activity The organization of the debriefing was also challenging during the first session dedicated to the levers activity. The teacher wrote down the examples generated by the groups in a rather disorganized way on the blackboard. As a result, the discussion was difficult to structure and guiding apprentices towards the discovery of the formulas was not easy. This issue was discussed during the lunch break between the two sessions and another approach was taken during the second session. The teacher first drew a lever on the blackboard and then wrote the examples given by the groups below it, placing values corresponding to pallets on the left or on the right according to their position on the lever. This new structure let the lever's formula appear more naturally, introducing visually the notion of equilibrium between left and right members.

Inducing the levers' law formula from a set of examples was difficult for the

Figure 7.38: Study 10: Debriefing session during the levers activity. The different examples generated by the groups have been copied below a lever.

apprentices. None of the groups managed to find it before the general discussion with the teacher. Some of the apprentices pointed out intuitive understanding, such as *"if the weight of a box is twice as much as another one, the distance doubles as well"* but could not express it in mathematical terms. Even after constructing the answer for the simpler formula limited to two pallets, generalizing the equation to an arbitrary number of pallets posed great problems to most of the groups. They relied on trial-and-error strategies to find the equilibrium point of levers with three pallets. We observed that some apprentices were switching the positions of the pallets too fast for the system to give a feedback and as a result did not manage to find the right position. The debriefing session was again crucial to get them to think about the problem in a more reflective way and identify generalizable patterns from several examples. The better representation adopted by the teacher made it easier for the groups in the second session to find the formula but still necessitated a good guidance from the teacher.

It is interesting to note that the teacher enriched the gravity center part with an additional step. He instructed the apprentices to draw a fork on their TinkerSheet to indicate how the each box should ideally be transported with a forklift (Figure 7.39). This proved to be a good way to get apprentices to use the examples they created to see the implications of this rather abstract notion for a concrete, everyday situation.

7.4.3 Discussion of Phase 4 studies

The two studies reported in this Phase took two different approaches to overcome the issues identified in the use of the Tinker Environment in a classroom context, with opposite results. Study 9 took a rather apprentices-centric approach. The written instructions distributed to each group were supposed to give apprentices more independence, reduce the time spent waiting for the teacher to give them instructions and encourage reflection during the activity through open-ended questions. As a result, the teacher would have more time to stop by each group and give them feedback and explanations whenever necessary. Study 10, on the con-

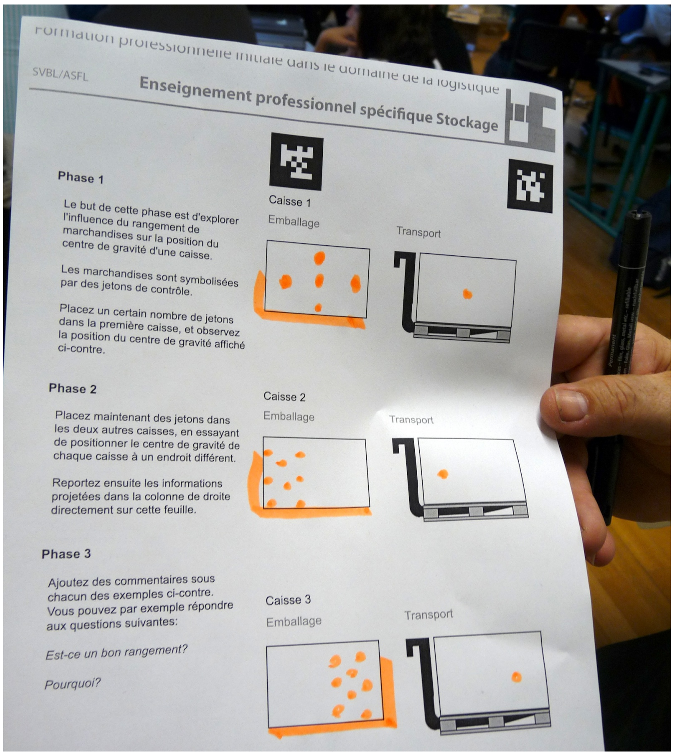


Figure 7.39: Study 10: The Integrated TinkerSheet used during the gravity center, annotated with the results obtained during the activity. It shows the adaptation made by the teacher to the scenario: apprentices drew a fork around left boxes to show how they would move the box with a forklift.

trary, put more emphasis on the role of the teacher as a coordinator of the activity, usually described by the concept of *orchestration* in the literature on collaborative learning [Dillenbourg, 2009]. The activities organized in this study put a strong emphasis on teacher guidance, class discussion and debriefing sessions. Interactions among apprentices, within groups and with the teacher take a central place. The interactions with the technological environments are used to create data that can later be used in discussions and compared to the solutions proposed by other groups rather than being the central aspect of an activity.

The teacher-centric approach taken during Study 10 proved to be more adapted to the context under consideration. The problems faced by apprentices and their lack of motivation observed in Study 9 has shown that apprentices need guidance and continuous monitoring to stay focused and engaged in the task at hand. Reading, understanding and acting from written instructions separated from the TinkerSheets where the tasks had to be performed (even more separated with the use of the small-scale model in the tangible condition) appeared to be beyond the organization and self-regulation skills of the apprentices. In these conditions, the questions supposed to trigger reflection in the instructions had no chance to reach their goal.

The attitude of the apprentices was different in Study 10: they seemed to be concentrated, focused and motivated by the task at hand. The constant encouragements, monitoring and explanations given by the teachers allowed each group to complete the activity in the allocated time. The design of the activity maintained a strong cohesion in the class because groups were assigned complementary tasks that would bring different results for the discussion concluding the activity (e.g. type of forklift in the surfaces activity or examples to generate in the levers activity). This gives a responsibility to each group to deliver a solution that will be useful for the whole class, and introduces in some occasion a certain competition among the groups that appeared to have a positive impact on the engagement and motivation level of apprentices. The teacher reinforced this feeling by ensuring that each group was progressing at a similar pace and encouraged comparisons among groups. The efforts put in the practical tasks increase the interest of apprentices during the discussion. They want to compare what they found to the solutions proposed by the other groups and are interested in understanding why their approach is better or not.

The design of the TinkerSheets also underwent a deep evolution during this phase that accompanied the implementation of teacher-centric activities. The Integrated TinkerSheets change the way the interface is understood: while the initial version of sheets focused on the interaction with the digital environment and organized the interface elements according to their functionality (e.g. sheet dedicated to floor visualizations or reorder strategy parameters of a product), the new design put a strong emphasis on their purpose as exercise sheets. Integrated TinkerSheets are specifically designed for a unique activity, as the following properties demonstrate it:

1. The interface elements available on a sheet correspond to the controls and feedbacks needed to perform the different tasks included in the activity;

2. The interface elements are arranged in a sequential way that respect the activity flow;

3. Enough empty space is provided to allow apprentices to write down their answers and comments and copy the information displayed by the Tinker Environment;

4. Instructions and reminders of theory are located next to the corresponding interface elements which facilitates their use both during the activity (no need to switch between different documents) and after for the debriefing session of the preparation of an exam for instance.

Integrated TinkerSheets offered a format adapted to the organization of the activity. The possibility to write down results directly on top of the sheets facilitated the transfer of information from the groups to the blackboard. While this can be done on any sheet of paper, the canvas offered by the TinkerSheets facilitates the copy by making it faster and more accurate since the digital information is directly copied. The overall observation is that Integrated TinkerSheets greatly facilitate the work of the teachers who can use the Tinker Environment in almost the same way as they do with traditional pencil-and-paper exercises. It allows them to guide the apprentices through experience and reflection phases. They distribute a paper document to the class, give some explanations, let the apprentices work for a while, give personal or general comments and explanations and finally ask several apprentices to write their results on the blackboard for a discussion. As we have observed during Study 10, the paper nature of the interface allowed teachers to modify the activity at the convenience. The computer does not have to be aware of the change since it can be arranged between the teacher and the apprentices.

Study 10 also demonstrated the importance of debriefing sessions to encourage apprentices to reflect about the practical tasks that are performed during an activity. The Integrated TinkerSheets facilitated the transfer of information from the groups to the blackboard. The move from a digital version of the information to the off-line world gave the teacher some freedom regarding the organization of the debriefing. While the first trials were not very satisfying, the teacher could adapt them for the next activity and improve the discussion by adapting it to the message to be transmitted. Again, the technology takes as much space as needed during the activity but leaves the space to more flexible and established procedures in the classroom.

Chapter 8

Results

THE CHRONOLOGICAL ACCOUNT of studies conducted either in authentic classroom contexts or in laboratory settings given in the previous chapter described the successes and issues encountered during the development of the Tinker Environment. As already pointed out, studies were not dedicated to a unique research question but usually contributed insight and evidence to answer several of them. In this chapter, we gather the results obtained during these studies to give an answer to the research questions addressed by this dissertation. The first three general questions concerned the affordances of Tangible and Paper Environments (TaPEs) in the three interaction circles defined in Chapter 4: individual, group and context. Questions 4 to 6 addressed more specifically the use of a TaPE in the context of the apprenticeship in logistics.

8.1 Question 1 - Complementarity

What is the complementarity of tangible and paper interactions in a tabletop environment?

Our model of TaPEs assumed that the Tangible User Interface (TUI) offers more direct and richer interactions than Interactive Paper Forms (IPFs), thanks to the physical affordances of tangible artifacts. IPFs are the result of a trade-off between directness and scalability which poses the question of the complementarity of these two interaction modalities and their impact on the overall quality of the interface.

8.1.1 Tangible components

The experiment reported in Study 2 confirmed the efficiency of tangible manipulation compared to a multitouch interface in a warehouse layout task. The results showed that participants in the tangible condition were faster than those in the multitouch in most of the situations. The tactile feedback offered by physical objects seems to play an important role: users can rely on tactile information to fine-tune the position of a shelf while focusing their visual attention on the next task. This aspect has been pointed out by [Fitzmaurice et al., 1995] who define it as a *visual interaction residue*. In comparison, interactions on multi-touch interfaces are limited to a visual feedback and force users to focus their visual attention on the objects they are manipulating. Another aspect concerns the physical affordances of the tangible shelves. Groups of shelves are moved using both hands to grasp them all at the same time while keeping their relative position and orientation. Users can also remove all the objects placed in the interactive area by pushing them away with their arm. These actions on tangible artifacts are more direct than similar interaction techniques implemented in the multitouch condition. Actions on digital objects first have to be captured by the input device and then translated to be applied to the objects. The interactions are thus limited to the type of actions implemented by the interface in the multitouch condition but are almost unlimited in the tangible condition since they take place in the real world only.

8.1.2 Paper components

Different interaction modalities were evaluated in Study 4: simple booklets with a fiducial marker printed on each page, used to move through the steps of predefined scenarios; a screen-based menu, operated with a keyboard on a nearby computer; a finger-based menu, controlled by pointing at projected icons on an A4 cardboard. These interfaces allowed us to identify several important dimensions for the design of a complementary interface to TUIs. Teachers did not find the use of fiducial markers to be an intuitive way to control the simulation and were thus often confused. We observed that they needed more freedom than the predefined scenarios could offer. The screen-based menu demonstrated that a physical distance between the two interaction modalities was detrimental to the flow of the activity. It was broken by the constant moves of the teacher between the table where the warehouse small-scale model was built and the menu on the computer. The finger-tracking menu failed mainly because of technical limitations which decreased the usability of the system. False positives led to an erratic behavior of the simulation and teachers did not want to use this interface since they did not feel in complete control of the environment.

The TinkerSheets, introduced in Study 5, brought a satisfying answer to these issues. The form metaphor on which their design is based proved to be powerful to facilitate their understanding by both teachers and apprentices. A short demonstration was enough to explain how tokens are used to interact with the interface elements provided by TinkerSheets. The physical proximity of the tangible and paper interfaces ensured a continuous interaction flow, allowing users to stay focused on the task at hand while quickly switching from one interaction modality to the other. TinkerSheets also suffered from some technical issues, usually due to an imperfect calibration. Given the problems encountered with the finger-based menu, they were surprisingly well accepted by the teachers. These issues forced users to move tokens slightly off the position printed on the TinkerSheet until the system detected it. As stated in Section 7.2.3, these false negatives were less negatively perceived than the false positives generated by the finger-based menu because the control stays in the hands of the users. The TinkerSheets did not trigger unwanted actions from the users who may in the worst case need some time to place tokens at the correct position.

8.1.3 Complementarity

We identified three types of interactions with TinkerSheets during the analysis of TaPEs conducted with the Instrumental Interaction model [Beaudouin-Lafon, 2000] in Section 4.1.3: activation, organization and action. Based on this analysis, we expected that IPFs would offer a lower degree of indirectness than the TUI, in particular for *actions*. Observations of apprentices and teachers working with the Tinker Environment confirmed these expectations. Setting parameters on a TinkerSheet took more time and efforts than manipulating a tangible artifact. Two main reasons explain these observations. First, the tokens used with TinkerSheets require an additional movement to grasp them and must be precisely placed on the interface elements. The problem is worse on the TinkerLamp because the small tokens used on this device are easily moved by inadvertence and tend to stick to fingers. The second reason is related to the lack of tactile feedback offered by TinkerSheets and is thus comparable to the results obtained in Study 2 concerning the multitouch condition. Users have to focus their visual attention on the token when they place it on a sheet.

The less direct interactions offered by TinkerSheets compared to the TUI did not appear to affect the usability of the system in a negative way. Neither teachers nor apprentices complained about the paper interface and we did not observe important problems. The main reason why TinkerSheets did not suffer from their lower degree of directness may come from the distribution of functionalities between the two interaction modalities. In line with our model for TaPEs, domain objects in the Tinker Environment are implemented by the TUI and IPFs are used to control secondary interface elements. This implies that users spend most of their time manipulating tangible artifacts which support rich and direct interactions. Tactile feedback and physical affordances are important for these tasks which demand precision and benefit from execution speed. TinkerSheets are primarily used to issue commands which do not have a clear tangible correspondence and, most importantly, are only occasionally used. This result illustrates one of the main principles of TaPEs, which achieve scalability through a trade-off between rich, direct interactions for crucial parts of the application and generic, slower interactions for secondary interface elements.

As we expected, the *activation* and *organization* interaction patterns benefited from the physical nature of TinkerSheets. The space around the interactive area of the system was heavily used during activities to store unused shelves and TinkerSheets. It worked as a kind of buffer that allowed apprentices to quickly move interface elements in and out of the digital world (e.g. *lookup* TinkerSheets described in Section 7.2.3). This behavior takes advantage of the dual existence of the paper and tangible elements in the digital and the real world: when an element is taken out of the interactive area of the system, it does not exist anymore in the digital world but still exists in the physical world. The physical proximity allows apprentices to quickly bring it back to the digital world, in a faster way than with Windows-Icon-Menu-Pointing devices (WIMPs) interfaces. In this later case, elements that have been deleted have to be recreated from scratch and may take some time, in particular if it is done through a menu. The physical buffer around the Tinker Environment facilitates quick deletion and creation of digital objects and gives a natural feeling to the whole interface. It is very similar to the way people work on a problem involving several objects, like a LEGO construction for example: the object being built is located in the middle of the group, the parts that are about to be used or have been removed lie around it while the ones that have not been used yet are still in the box.

8.2 Question 2 - Effects on collaboration

How does a TaPE impact group interactions during collaborative problem-solving activities?

Study 3 demonstrated the positive impact of the tangible small-scale model compared to a multitouch interface on the quality of collaboration and perceived level of playfulness of groups working on a warehouse layout task. The more direct interaction modality and tactile feedback offered by the TUI may explain these better results because it requires a lower level of cognitive effort. Apprentices in the multitouch condition spent some of their energy focusing their attention on the interface rather than on the problem at hand. The TUI probably allowed the participants to save this energy and put more efforts on the resolution of the problem and the collaboration with their peer. The possibility to focus on the problem and interact in a more direct way with the warehouse model also explain the higher level of playfulness experienced by the apprentices in the tangible condition.

While TinkerSheets were not used to control the simulation during this study, we argue that these results can be extended to TaPEs because of the complementarity of the paper and tangible interaction modalities at the individual level. As discussed in the previous section, TinkerSheets did not have a negative impact on the quality of interactions on the Tinker Environment because of an adequate distribution of features among the tangible and paper interaction modalities. The less direct interaction modality offered by TinkerSheets should then not have an impact at the group level either.

The different types of interfaces evaluated during Study 4 highlighted some of the potential issues of a complementary interface to a TUI regarding group level interactions. The screen-based and the finger-based menus' single-user nature is not adapted to a collaborative situation. The screen-based menu was projected on the interactive area of the environment and thus interrupted the whole group when it was in use. Limiting the display of the menu to the computer screen would have solved this problem but would have removed the visibility of the actions performed by the user controlling the menu from the rest of the group. Social rules also proved to be an issue for the choice of a complementary interface: apprentices did not dare to use the screen-based menu since the computer was perceived as reserved for the teacher. The finger-based menu was then used only by the apprentices who were more at ease with the usability issues of its implementation than their teachers.

TinkerSheets do not suffer from these limitations. Their physical nature and the possibility to use them in any position and orientation in the interactive area allow them to support collaborative situations in a natural way. Compared to a menu, they allow users to control and/or visualize different parameters at the same time, either on the same sheet or by arranging several of them in the interactive area.

Another interesting property of TinkerSheets is their visibility: each group member can see which actions are about to be taken on a sheet and interrupt whenever necessary. The printed content of a sheet helps users recognize it and identify which parameter is displayed even if the text is not readable from their position.

Interestingly, our observations during Study 5 showed that apprentices did not use much the possibility to share TinkerSheets and place them in any position. The competition for space between the small-scale model and the sheets partly explains this behavior. Another reason we hypothesized was that apprentices tended to specialize in different roles, with some peers doing most of the warehouse layout and others monitoring values on TinkerSheets. We observed that a given TinkerSheet was often used by a unique apprentice during a session. An analysis of eight groups working on the Tinker Environment during the sessions reported in Study 5 confirmed a strong tendency among apprentices to interact with interface elements close to them. The position of team members around the system and the placement of interface elements thus have an impact on group interactions. Apprentices take implicit roles focused on the *construction* of warehouses or the *monitoring* of relevant indicators.

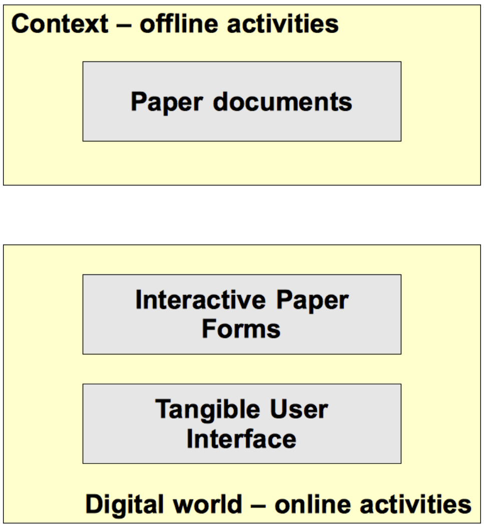


Figure 8.1: The situation with the first design of TinkerSheets, which focused on their *interface* nature. They belong to the digital world and activities organized around the Tinker Environment are disconnected from the paper-centric classroom context.

8.3 Question 3 - Integration

How does a TaPE integrate in a classroom ecosystem?

The observations of the Tinker Environment during its use in classrooms confirmed the crucial role that IPFs play in the integration of a TaPE in a classroom (context

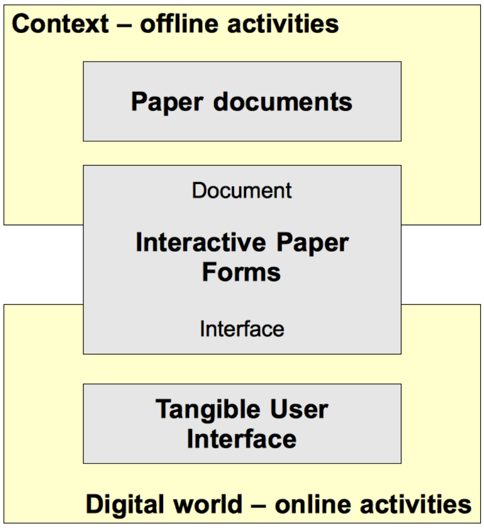


Figure 8.2: The situation with the introduction of Integrated TinkerSheets. Their design focuses on their *document* nature and allows them to go beyond the digital world and act as a bridge between online and offline activities. They exist in the classroom context where they are considered as traditional exercise sheets.

interaction circle). The Design-based Research (DBR) studies conducted with different versions of TinkerSheets demonstrate that both have to be carefully designed for the integration to be successful. TinkerSheets have a dual nature: they can be considered as an interface, used to interact with the Tinker Environment, but can also play the role of documents such as exercise sheets.

The **first version** of TinkerSheets focused on their *interface* nature and they were used as such by the teachers and their apprentices. Since an interface belongs to the digital world, it was exclusively used to control the environment as we could observe during Study 5. The arrangement of interface elements was mostly done in a logical way: elements related to a similar functionality were put together and each sheet was filled with as many parameters as possible. They provided a satisfying solution to the scalability issue of TUIs, according to their primary design goal, but apprentices and teachers did not use them to write down results and annotations during the activities as we expected. Figure 8.1 illustrates the situation with this first design: activities taking place around the Tinker Environment were disconnected from the offline classroom activities based on paper documents. TinkerSheets were part of the digital world and shared a similar status with the warehouse small-scale model: they were an interface and no more.

Similar TinkerSheets were in use during Study 9 but were accompanied by written instructions, distributed on separate sheets. Different factors played a role in the failure of this study, but the separation of instructions from the TinkerSheets were partly responsible for the disappointing outcome of this activity. With this approach, the results written on a TinkerSheet during the activity did not have much value afterwards because they could not be easily related to the instructions which produced them.

The **second design**, Integrated TinkerSheets, places a stronger emphasis on the *document* nature of TinkerSheets. Sheets are not conceived as an interface anymore but as exercise sheets. The interface elements they contain correspond to the parameters needed for a given activity and are organized in a way that is adapted to the expected flow of the activity. Figure 8.2 illustrates this new situation. TinkerSheets go beyond the limits of the digital world and now exist independently as paper documents in the offline classroom context. Their dual nature allows them to be used as an interface to control the simulation running on the Tinker Environment and their document nature makes them suitable to capture results and reused them in offline situations. Written instructions are embedded on the document and give a meaning to the annotated results. Integrated TinkerSheets act as a bridge between online and offline contexts. They support a continuity of actions among these two situations, allowing seamless transitions between online and offline parts of an activity.

Figure 8.2 offers a different view of TaPEs than the model we introduced in Chapter 4, based on the distance between user actions and the digital objects. The TUI is at the core of the interaction with the digital world, providing users with high a degree of directness. IPFs are trade-off between directness and scalability: interactions are less direct but allow the tabletop environment to handle applications of any complexity, as is the case with the logistics simulation implemented on the Tinker Environment. The surrounding context is usually disconnected from the activities taking place in the digital environment. This was for instance the case of the classroom with the first design of the TinkerSheets. TinkerSheets solve the scalability issue because they offer a generic set of interaction primitives. This genericity, coupled with their paper nature and the final integrated design, allowed them to bridge this barrier and connect these two disconnected activity levels. Activities taking place in either of them could than go beyond their boundaries and seamlessly move between online and offline contexts.

It is interesting to note that no additional technological development was done between the two TinkerSheets designs. The modifications were done at the level of the printed content: interface elements were simply rearranged to adapt the interface to the existing practices and integrate it to the pre-existing paper documents.

Study 10 showed that TinkerSheets allow the Tinker Environment to become part of the classroom ecosystem by making it compatible with existing practices. In this last study, the use of the system was almost transparent for both teachers and apprentices because the organization of the activity was very similar to a traditional pencil-and-paper exercise:

1. Groups of apprentices are formed and the teacher distributes the instructions on a sheet of paper;
2. Apprentices read the instructions, listen to the instructions of the teacher and then start working on the problem;
3. The teacher moves from one group to the other, gives advice and explanations when needed, ensures that their progress follows the rhythm of the others

and makes general comments to the class;

4. The groups share their solution, which was written during the activity on a sheet of paper with the class, possibly copy it on the blackboard;
5. The teacher uses the solutions to organize a debriefing that makes a synthesis of the findings and the apprentices finally store the documents in their folder.

The only difference between an activity with the Tinker Environment and traditional paper-based exercises lays in the use of a simulation that is controlled by the instructions sheet. The small-scale model could perfectly be used in a traditional exercise session and is thus not specific to a technology-enhanced context. This similarity is possible because TinkerSheets hide the complexity of the computer and avoid potential issues. When they receive the instructions, apprentices do not have to locate the right application on the computer, launch it and then navigate through a menu to load the activity; they simply show the instruction sheets to the system which loads the corresponding application with the right parameters. Potential issues such as printer or network connectivity are avoided because the design of the activity limits the use of technology to the minimum needed and relies rather on existing practices: the results are neither printed nor sent automatically to the teacher computer but are directly written down on the instruction sheet by the apprentices. Even though it might be less efficient than a richer technological approach, it removes as much computer-related management as possible and allows teachers and apprentices to focus entirely on the task at hand.

8.4 Question 4 - Small-scale model

Does a warehouse small-scale model help apprentices in logistics to better understand theoretical concepts?

The potential of the warehouse small-scale model for apprentices in logistics was immediately recognized by the teachers during the first informal trials of Study 1. They were positively surprised by the level of engagement of apprentices, in particular the ones who are usually passive, and the very short time needed to produce a warehouse layout compared to pencil-and-paper activities. The observations conducted in a classroom during a traditional paper-based warehouse layout problem illustrated the difficulties faced by the apprentices when presented with an open-ended problem. Most of the groups apparently lacked the necessary spatial representation skills to handle the problem. They were stuck for a long time in front of a blank blueprint because they did not know how to engage into the activity and decompose the problem into smaller pieces that are easier to address. These difficulties had a negative impact on the motivation of apprentices and the solutions they produced, who were usually not satisfying according to the teachers.

In contrast, activities organized with the tangible environment reduced the difficulty of the problem and allowed apprentices to engage in the activity and put energy into the design of an efficient warehouse. The size of the problem-space is smaller with the small-scale model compared to the pencil-and-paper activity because several variables are fixed and the production of solutions is facilitated. The scale issue is removed: the size of the warehouse floor as well as its elements such as shelves and rooms is given and does not have to be chosen by the apprentices. It is also easier for apprentices to create a layout using physical artifacts than with a pencil and a ruler. We observed that most of them were not able to sketch and spent a lot of time precisely drawing the elements of the warehouse. The solutions produced with the small-scale model were not necessarily better, but the time invested in the task was much shorter and saved time for more trials and class-wide comparisons and discussions. The lower complexity of the problem proposed in the tangible condition was thus adapted to the skills of the apprentices. It reduced the number of variables and made the problem tractable for them. While it does not improve apprentices' understanding of proportions because the scale issue has been removed from the task, it allows them to engage in meaningful problem-solving activities. The tangible approach bridges the abstraction gap because it facilitates engagement by adapting the problem complexity to a level that allows apprentices to engage in the task.

Controlled experiments conducted in laboratory settings comparing the small-scale model to a multitouch interface confirmed the qualitative observations gathered during Study 1. Study 3 results showed that the tangible condition led to a higher learning gain and also increased the performance and collaboration quality of the participants. The main factor explaining these results was the number of solutions explored by dyads. It gave an advantage to the tangible condition which was shown to be faster than the multitouch interaction modality in the usability experiment conducted in Study 2.

A hypothesis that motivated the use of the small-scale model was that the concrete representation it offers is closer to the everyday experience apprentices have at their workplace and may facilitate the understanding of theoretical concepts. While it is difficult to draw a clear conclusion from our observations, the practice field created by the tangible model appears to have a positive impact on the discussions related to the warehouse layout. The drawings collected after the paper-based activity we observed show that the interpretation of proportions from a 2D blueprint is difficult for apprentices. The fact that they were unable to detect obvious flaws in their designs also demonstrates that they could not transfer the drawings to a representation that would let them run mental simulations. In the tangible condition, apprentices seem to be able to better link the model to an actual warehouse and can thus predict potential problems. We observed remarks among group members, such as an apprentice commenting on the position of a shelf just placed by a peer, as well as comments during discussions with the teacher. A good example of this later case is an apprentice who engaged in a rather long and elaborated description of the position of the docks in his company.

To sum up, the studies conducted with the Tinker Environment identified three factors which show the potential of the warehouse small-scale model as a way to bridge the abstraction gap. First, it reduces the complexity to a level adapted to the skills of apprentices. Second, it allows them to solve problems faster and leaves time for more trials and most importantly discussions about the proposed solutions. Third, it provides a concrete, meaningful representation of a warehouse that can be used by apprentices to run mental simulations and detect potential issues.

8.5 Question 5 - Concrete to abstract representations

Does a TaPE support apprentices in the transition from concrete to abstract representations?

The activities developed for the Tinker Environment and observed during Studies 6 to 8 illustrate how the complementarity of tangible and paper components of TaPEs can be used to control the level of representation presented to apprentices. Each activity provides Multiple External Representations (MERs) that include both concrete and abstract representations. Concrete representations (usually the warehouse small-scale model) reduce the difficulty for apprentices to engage in the task and are linked to the theory presented at school by the abstract representations. Besides the different levels displayed within each activity, the Tinker Environment also provides apprentices with a progressive move from simple, embodied concepts to more abstract, disembodied theoretical aspects.

At the beginning of the apprenticeship, the main topic concerns the physical organization of a warehouse and is reflected with activities where the attention of the apprentices is focused on the manipulation of the warehouse small-scale model. TinkerSheets display information that mirrors observable properties of the layout such as the number of available storage positions (alley width activity, Study 6). The surface activity observed during Study 7 takes place in the middle of the curriculum. It is still centered on the physical model but the data presented on TinkerSheets is less directly observable from the warehouse layout. The graphical and numerical representations of surfaces are directly related to the physical organization of a warehouse but correspond to an abstract layer placed on top of a blueprint to analyze the efficiency of the organization. Activities taking place towards the end of the curriculum, such as the storage management activity observed during Study 9, do not necessarily involve a warehouse layout task. The concepts that are addressed at this level are not directly connected to a particular layout anymore. The concrete representation is not given by the physical model but by a down-scaled projected warehouse layout. The data displayed on TinkerSheets is not directly observable on the warehouse because it includes both historical information (e.g. storage levels of the last two months) and invisible aspects such as storage breaks.

The observations conducted during Phase 3 studies provided some evidence that the level of representation offered by the Tinker Environment at different points of the curriculum was adapted to the skills of apprentices. They were able to engage in problem-solving activities during each of these studies, ranging from basic, concrete concepts related to warehouse layouts, to more complex and disembodied notions such as storage management strategies. The capacity demonstrated by the apprentices to interpret and use the information displayed on the TinkerSheets did not mean that apprentices were reflecting on their actions and get to a real understanding of the underlying concepts. We observed that groups tended to apply the same trial-and-error strategies they used with the small-scale model to react to the more abstract representations given on TinkerSheets. Observations conducted during Study 8 showed that apprentices could read storage level curves but did not reflect on the corrective measures that had to be taken in difficult situations. They rather relied on their intuition to change parameters and solve the problem.

The activity designed for Study 9 attempted to overcome this issue by providing apprentices with instructions that aimed to structure the activity and encourage apprentices to reflect about the results found with the simulation. This study suffered from the fact that teachers did not play an active role and rather left the apprentices organize their work. The objective of the written instructions was to give some independence to the groups and allow them to go through the tasks they were assigned without having to wait on the teacher to tell them what to do. We observed that the groups were not able to regulate themselves: most of them did not complete the activity and did not follow the written instructions. Reflection prompts were ignored by most of the apprentices who rather played with the system without performing the required tasks. These results demonstrated the need for a strong guidance of the teacher to drive apprentices through the activity and the necessity to organize debriefing sessions to discuss the practical results obtained with the Tinker Environment and encourage apprentices to reflect about them.

The final design of TinkerSheets tested during Study 10 finally reached this objective. The guidance provided by the teacher during the activities we observed ensured that all the groups performed all the required tasks. The debriefing sessions demonstrated that apprentices were able to use the abstract representations displayed on the TinkerSheets and copied on the classroom blackboard to answer questions related to the concept taught during the lesson and reflect about it. In the pencil-and-paper activity observed during Study 1, apprentices were not able to detect obvious flaws in a 2D blueprint of a warehouse. The debriefing session organized after the surfaces activity observed during Study 10 demonstrated that apprentices were able to criticize and detect issues in the layouts created by other groups and displayed as 2D blueprints. While it does not constitute a definitive proof, it is nonetheless a good indicator that they were able to better interpret a more abstract representation after working on a concrete representation (the warehouse small-scale model).

8.6 Question 6 - Role of the teacher

What is the appropriation process of a TaPE for teachers?

Teachers play a central role in a TaPE, as demonstrated by Study 10. They drive the activity, check that all the groups are progressing at the same pace, encourage and help apprentices whenever needed, manage debriefing sessions and guide the class towards the objective of the lesson. Study 9 was a good example showing the consequences of the absence of the teacher as the conductor of the activity: apprentices loose motivation, do not perform the tasks assigned to them and do not reach the learning objectives of the activity. The term *orchestration* is often used in the literature to refer to the design and the management of activities taking place in the classroom [Brophy and Good, 1986, DiGiano and Patton, 2002, Dillenbourg and Fischer, 2007]. As discussed by [Dillenbourg and Jermann, 2010], the use of this metaphor is misguided since orchestration in the musical sense means writing down the music score that an orchestra will have to play, while managing a classroom demands real-time adaptations to cope with learning opportunities arising during a class activity. As we expected, the appropriation of the Tinker Environment by the teachers was a two way process. On one hand, teachers had to adapt their teaching style to the pedagogical approach fostered by the environment, based on collaborative ill-defined problem-solving activities. On the other hand, the system had to be tailored to support the teachers and adapt to the curriculum constraints, providing the right level of flexibility for the integration to take place. We develop these two processes below.

On the teacher side, the prevailing teaching approach before the introduction of the Tinker Environment was based on a transmission of knowledge from the teacher to the apprentices. Typical exercises or problems solved during the class used to be well-defined and offer a unique solution. The shift towards a constructivist approach, based on open-ended problem solving activities on the Tinker Environment implied for the teachers a redefinition of their role. As reported in Study 1, they observed that improvisation takes a larger place in the activities since the solutions proposed by the apprentices to a problem can not be predicted but still have to be used to guide them towards the objective of the activity.

A particularly challenging question for the teachers was to find the right level of control they should keep during an activity. It was interesting to observe how this adaptation took place over the 10 studies conducted with the Tinker Environment. During the first session that took place on the university campus with two groups, the two teachers adopted a very directive style, guiding the apprentices through the problem-solving task in a tight way. After reflecting on this first session during the lunch break, they tried to give more freedom to the next groups. The outcome of these first trials was that the right balance probably lies between these two extremes. On one hand, too much control reduces the potential richness of the activity because apprentices do not have the chance to explore the solution space. On the other hand, leaving too much independence to the apprentices is not optimal neither because they are not able to regulate and motivate themselves, as confirmed by Study 9.

The right balance was finally found in Study 10. In the sessions we observed, the teacher kept a tight control over the organization of the activity, but apprentices were free to develop their own solution to the problem. The teacher had a clear objective in mind regarding the concepts to address during the session and was able to use the solutions proposed by the different groups to guide the discussion in the right direction and encourage the apprentices to reflect on these concepts.

The Tinker Environment, in turn, had to be adapted to the needs of the teachers and support orchestration. It happened in three ways.

First, the pre-existing curriculum for the apprenticeship in logistics guided the development of the Tinker Environment. Since the curriculum defines the pedagogical objectives that teachers have to reach with their apprentices, the possibility to fulfill these objectives with the environment was a necessity. The involvement of logistics teachers in the development process was crucial to ensure that the activities offered by the Tinker Environment were adapted to the curriculum. The digital content and the way to present it were adapted to the existing documents, reusing for example the same type of representations to display warehouse surfaces or storage level charts. Without this adaptation of the system towards existing practice, the teachers would not have adopted the environment.

Second, the Tinker Environment had to provide the right level of flexibility to support teachers during activities. We observed in Study 4 that strictly pre-defined scenarios were not adapted. The interface based on fiducial markers, arranged in a booklet and used to move from one step of an activity to the next, did not give enough freedom to teachers. They were forced to follow a pre-defined sequence and had no way to adapt the activity to their needs. Some flexibility would have been useful to address questions raised by apprentices or to modify the scenario to respect time constraints. The introduction of TinkerSheets brought some flexibility to the teachers but also removed the structure of activities. Each TinkerSheet contained many parameters and offered many opportunities for apprentices to set a wrong parameter or perform other tasks than those asked by the teacher. These sheets did not give enough control to the teachers. They had to compensate for the absence of any scenario and spent too much time giving instructions to each individual group and checking whether the right parameters were set. Integrated TinkerSheets provided a better level of flexibility, introducing again the notion of scenario while leaving some freedom for the teachers to adapt the activity to their needs. Compared to the early hard-coded activity sequence provided by the fiducial markers-based interface, Integrated TinkerSheets define scenarios in a flexible way. Interactive elements are arranged on the sheets in a way that reflects the expected activity flow, next to printed instructions, but does not force users to follow the structure. Nothing prevents apprentices to use any interactive element printed on an Interactive Tinkersheet at any time, but teachers keep a better control on the activity because of the limited number of elements. The sequential presentation is easier for apprentices to follow and facilitates guidance by the teacher.

Finally, the Tinker Environment provides flexibility in the organization of activities in two other ways. It does not force the teachers to follow the pedagogical approach it encourages, based on collaborative ill-defined problem-solving activities. For instance, it was possible to set up a tightly controlled activity in Study 6. Teachers forced the apprentices to place the shelves in a fixed orientation. The reason for this constraint was an attempt to get a total control of the activity by knowing in advance the solution to the problem. The teacher measured the amount of shelves that could be placed in the warehouse for each step of the activity. Unfortunately, the apprentices did not necessarily find the perfect solution to each problem and it was then difficult for the teacher to comment on the results and guide the discussion towards the concept he wanted the apprentices to understand in this activity. In this case, we see that since the environment was developed with a specific pedagogical approach in mind it does not necessarily work well in other settings.

The physical nature of a TaPE provided teachers with interesting ways to repurpose the system and adapt the activities on the fly. We saw an example in Study 10, during the gravity center activity. Apprentices were instructed to add annotations to the TinkerSheet, indicating from which side they would carry a box with a forklift. The paper nature of TinkerSheets allows teachers to go beyond the functionalities offered by the system, giving apprentices instructions that the environment is not aware off. This example illustrates another positive effect of the continuity between digital and offline contexts offered by TinkerSheets. Teachers can extend activities taking place on the Tinker Environment with traditional, paper-based offline activities.

In summary, the Tinker Environment has been appropriated by teachers through a sequence of mutual adaptations, i.e. through an evolution of both the design of the tool and the pedagogy of teachers.

Chapter 9

Conclusion and perspectives

THE COMPLEMENTARITY of tangible and paper components and their impact on interactions taking place around a collaborative tabletop environment is the central topic addressed by this dissertation. We proposed the use of Interactive Paper Forms (IPFs) as a secondary interaction modality in a tangible environment to address two main shortcomings of Tangible User Interfaces (TUIs). The scalability issue concerns the mapping of software functionalities on tangible artifacts, particularly challenging for complex applications. The pedagogical issue is related to the difficulty to teach abstract concepts using physical manipulatives. We introduced the notion of Tangible and Paper Environments (TaPEs) and evaluated their potential in the context of the Swiss dual vocational training system. We co-developed with two logistics teacher the Tinker Environment, a TaPE composed of a warehouse small-scale model (TUI) and TinkerSheets, our implementation of IPFs. Design-based Research (DBR) studies were conducted on a regular basis in several professional schools and were complemented with controlled experiments.

9.1 Summary

9.1.1 Scalability issue

TaPEs overcome the scalability issue thanks to the set of generic interaction primitives offered by IPFs. A trade-off is made between the rich physical affordances of a task-specific TUI and the less direct but scalable interaction modality offered by IPFs. We proposed a descriptive model of TaPEs that illustrates the complementarity of paper and tangible components not only at the individual interaction level but also at the group and context levels, represented as three interaction circles. The three general questions addressed by this dissertation concern the unique affordances of these two interaction modalities and their impact in these different interaction circles. The studies conducted with the Tinker Environment showed that TinkerSheets offered a good quality of interaction despite their lower degree of directness. We argued that the main reason was the good distribution of functionalities among the tangible and paper components and proposed a design guideline for the development of TaPEs. Objects or parameters that imply continuous, precise interactions should be implemented by tangible components (e.g. shelves). IPFs are adapted for discrete interactions that do not represent a significant amount of user actions during normal system use (e.g. simulation control or choice of the type of forklift). At the group level, the shared physical nature of tangible and paper components naturally support collaborative situations. The main impact on group interactions concerned the creation of implicit roles based on the position of apprentices around the environment. We finally observed the potential of IPFs for the support of seamless transitions between the digital environment and offline activities taking place in its surroundings. In the classroom context, annotations on TinkerSheets allowed apprentices to capture data displayed by the logistics simulation and make it available for debriefing sessions. The studies illustrated the dual nature of IPFs as interfaces and documents. The first design of TinkerSheets emphasized their interface nature and implicitly limited their use within the digital context. The document-oriented Integrated TinkerSheets gave them the same status as traditional paper exercise sheets and allowed them to bridge the digital barrier and become used during offline classroom activities such as debriefing sessions.

9.1.2 Pedagogical issue

We identified an abstraction gap during an initial field study in the logistics apprenticeship context. The gap comes from the too theoretical presentation of concepts in schools and the fact that apprentices do not have the opportunity to apply these concepts at their workplace. We proposed a pedagogical approach taking advantage of the properties of TaPEs. The TUI takes the form of a warehouse small-scale model that creates a practice field where apprentices explore theoretical concepts in practical situations. Multiple External Representations (MERs) were used to link the concrete representations offered by the small-scale model to the more abstract representations that apprentices should understand and be able to use. Abstract information is displayed on TinkerSheets, thanks to the capacity of paper to act as a generic information container. The approach does not only use MERs to display different levels of representation within a given activity but also fosters a progressive move during the curriculum towards more complex and disembodied concepts. The dual interaction modality offered by TaPEs is used to implement this progression: the focus is placed on the small-scale model at the beginning of the curriculum but the abstract representations provided by TinkerSheets are progressively more emphasized to the point where tangible components are not used anymore (e.g. storage management activity).

Three specific research questions were posed, regarding the small-scale model and its capacity to bridge the abstraction gap, the support of a smooth transition from concrete to abstract representations by a TaPE and finally its impact on the role of the teacher. The studies conducted with the Tinker Environment showed that the warehouse small-scale model contributed to bridge the abstraction gap by allowing apprentices to engage in problem-solving activities. We observed that traditional pencil-and-paper activities were too complex for apprentices who did not manage to handle the task. They had great difficulties to produce layouts because too many variables had to be considered simultaneously. They were unable to interpret 2D blueprints as the representation of a real warehouse and did not detect obvious flaws in their solutions.

The level of representations displayed on TinkerSheets during activities at different stages of the curriculum was adapted to the needs of apprentices. They were able to understand them and use them during problem-solving activities. A closer look at the strategies applied by apprentices to develop solutions demonstrated they were mostly found with a trial-and-error approach. Simply presenting apprentices with MERs at different levels of abstraction did not overcome the issue often observed with the use of physical manipulatives in learning situations. Apprentices tended to stay at a concrete mode of reasoning and did not reflect about the activity. The organization of debriefing sessions was necessary to overcome the problem.

The studies highlighted the crucial role of the teacher in the use of the Tinker Environment. We observed that without the teacher, apprentices appeared to lack the necessary self-regulation skills and did not perform the expected tasks. Teachers need to drive the activity, constantly check that the groups are following the pace, give advice and explanations to some apprentices and, most importantly, have to integrate the different solutions and guide the discovery of important concepts during debriefing sessions. The successful integration of the Tinker Environment in classrooms was the result of a combination of factors but could not happen without the central role of the teacher as the driver at the center of the activity.

9.2 Discussion

9.2.1 Parallels among pedagogical and interactional issues

An interesting parallel can be made among the way TaPEs were used to overcome the scalability and pedagogy issues of TUIs in collaborative tabletop environments. The use of a specific TUI improves the quality of interactions thanks to their rich physical affordances. The same specificity was used in a pedagogical context to offer a concrete representation of a warehouse to apprentices in logistics. Scalability is made possible by the use of IPFs which implement a task-independent, generic interface modality. This capacity comes from the possibility for paper to act as a generic information container, which was used in turn to display abstract, disembodied representations on TinkerSheets to apprentices. Finally, the tighter integration of TaPEs in their context supported by the affordances of paper were crucial to facilitate the role of the teacher and enable the organization of meaningful debriefing sessions. We presented another view of TaPEs in section 8.3, based on the notion of distance between user actions and digital objects. This view illustrates how IPFs act as bridges between two usually disconnected contexts, the digital world and paper-centric offline activities. The same view can be used to illustrate the role of TinkerSheets as bridges between the concrete representations offered by the practice field and the abstract, disembodied representations presented at school. Information displayed on TinkerSheets lies at a higher level of abstraction than the augmentations projected on top of the small-scale model. They correspond to an intermediate step displaying dynamic representations before being captured through annotations and become static representations during offline activities. The two roles of TinkerSheets as bridges between the digital world and the classroom context are illustrated on Figure 9.1.

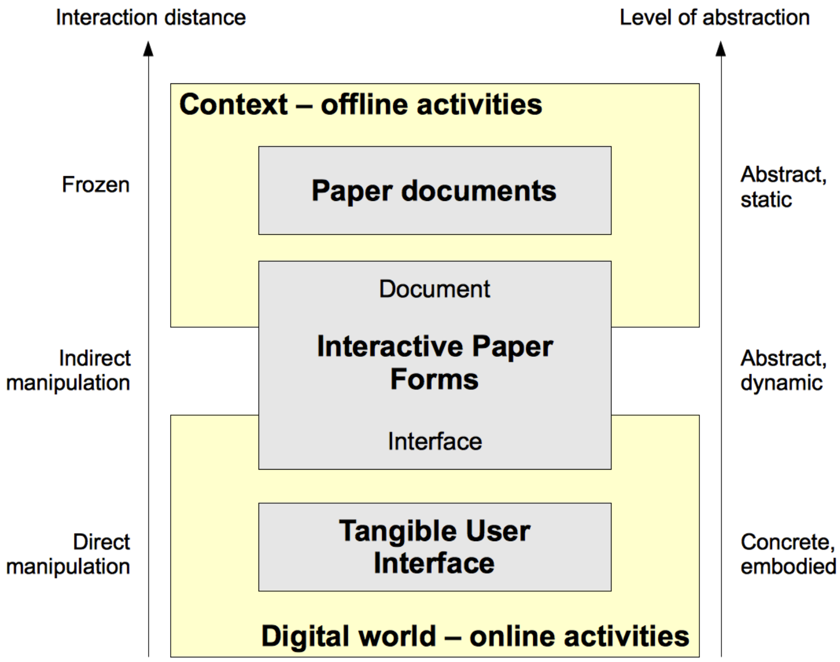


Figure 9.1: An integrated view of TaPEs illustrating the double role played by IPFs as bridges between the digital and offline activities in terms of interaction distance and level of abstraction.

9.2.2 Complementarity of controlled experiments and DBR studies

The hybrid methodology adopted for this dissertation, mixing both DBR studies conducted in authentic classroom settings and controlled experiments was adapted to the study of our research questions. Controlled experiments were useful to evaluate the impact of specific aspects of the Tinker Environment away from the noisy classroom context. The interesting results obtained during the two controlled experiments that compared the use of the small-scale model to a multitouch interface in a warehouse layout task would have been difficult to obtain through DBR studies. Observations conducted in an authentic context are influenced by many variables that are impossible to control, such as class and teacher effects. The outcomes can not be attributed to a unique variable and interesting effects may be hidden by other random factors.

The disappointing results obtained in Study 9 illustrate the difficulty to transfer laboratory results into authentic practice. No difference was found between apprentices using the small-scale model and apprentices working on an equivalent pencil-and-paper problem. More surprising, the learning gain was close to zero in both conditions despite the similar difficulty of pre- and post-tests. We have pointed out several reasons explaining these results, such as the fact that teachers did not actively teach, the difficulty for apprentices to follow instructions written in a 10 pages long document or their lack of motivation. All these reasons certainly contributed to the results obtained during this study but there is no way to get a quantitative comparison of their respective influence. More importantly, the differences between the small-scale model and pencil-and-paper activities may simply not be observable after a two-hour session. The amount of noise captured in such an authentic context is probably higher than any measurable quantitative difference. Longer-term longitudinal studies are better suited to assess the capacity of the Tinker Environment to support the acquisition of abstraction and problem-solving skills for apprentices in logistics.

9.3 Perspectives

The solution to the scalability and pedagogical issues of TUIs proposed in this dissertation is not limited to the context of the apprenticeship in logistics. The complementarity of paper and tangible components in TaPEs, assessed through studies conducted in authentic classroom contexts, supports the implementation of arbitrary complex applications in collaborative tabletop environments. TinkerSheets, our implementation of the concept of IPFs, have been developed as a generic interface that can be used as a complementary interface to any TUI. The main constraint of the current implementation concerns the tabletop environment which has to be based on front-projection to be able to augment paper sheets with digital information. Different approaches may loose the ability to implement IPFs on traditional paper documents but be nonetheless adapted to specific situations (e.g. Anoto paper). Beyond the scalability issue, the analysis of the impact of TaPEs at different levels of interaction demonstrated the potential of paper as an interface to control and visualize a software application and highlighted the advantages provided by its unique affordances. Actions at the individual level are less direct and rich than the physical manipulation of tangible artifacts but the physical nature of paper places IPFs at the same level of TUIs for the manipulations of the interface itself (activation and organization, Section 4.1.3). The unique advantages of paper become clear when one considers the integration of the tabletop environment in the offline activities taking place around it. IPFs can be adapted to take the form of paper documents already in use and support seamless transitions between online and offline activities.

The pedagogical approach developed for the apprentices in logistics also has implications that go beyond this specific context. The benefit of a concrete representation to facilitate the engagement in learners in problem-solving activities is not only useful for apprentices in logistics but may be applied in any learning situation fostering exploration and discovery. The possibility to display Multiple External Representations (MERs) addresses a generic need to lead learners to more abstract representations. Finally, the overall organization of activities organized around the Tinker Environment, including both free exploration in groups and class-wide discussions and comparisons can be applied in any learning situation. The role of the teacher is central for the successful integration of such an environment in a classroom setting even though it may slightly vary depending on specific situations. For instance, learners in other domains or at different levels do not have the same self-regulation and problem-solving skills and may not need the same amount of guidance from the teacher.

It would be interesting to see how TaPEs can be integrated into contexts other than classrooms. The possibility offered by TaPEs to use complex applications on collaborative tabletop environments allow them to consider their use in a professional context. These environments are obviously not suited for replacing existing personal computers but may find their place in collaborative problem-solving situations. TaPEs support a smooth integration of the environment in the activity, allowing participants to work as usual with pre-existing documents but also explore potential solutions on the TaPE. Promising solutions are captured on IPFs via quick sketches, integrated into the pile of traditional documents and/or sent to a network repository where the person responsible for implementing the chosen solution using a personal computer.

We can also imagine other types of applications where IPFs take a more central role. Typical scenarios include customer relationships situations where a consultant explains the advantages of products or solutions offered by a company. An interactive lamp located on a regular meeting table is used to augment presentation booklets and enrich the discussion. Simple tangible controls allow both the advisor and customers to set parameters of simulations associated with printed content, adapting them to the situation of customers and testing different options. Annotations or a nearby printer capture interesting results that can be taken home by users to think again about the proposed solutions. Access to the simulation is still possible: showing the booklet to the webcam of their computer or any other computational device points a web browser to an online version of the software. This scenario is close to Weiser's original vision of *Calm Technology* [Weiser and Brown, 1997]: the computer is embedded in the environment but only becomes at the center of attention when needed. The crucial difference, which follows Rogers' call for proactive users rather than proactive computers [Rogers, 2006], is that **people decide** when and how they want to switch from an offline activity to the digital world.

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Appendix A

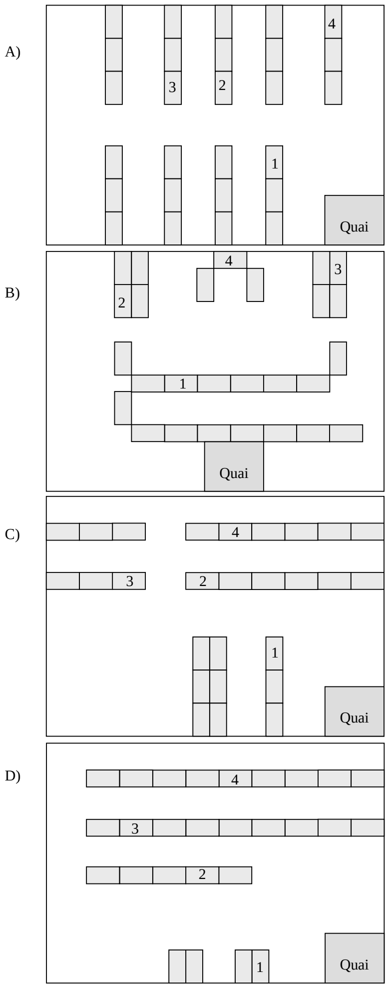
Tests and questionnaires

A.1 Study 3 documents

The documents distributed to apprentices during Study 3, described in Section 7.1.3, are reproduced over the next pages:

1. the pre-test;
2. the post-test;
3. the final questionnaire.

A.1.1 Pre-test



Voici quatre entrepôts A, B, C et D ; chacun contient le même nombre d'étagères (40) et dispose d'un quai de réception et d'expédition. Les numéros 1, 2, 3 et 4 sont quatre palettes à sortir de l'entrepôt.

Exercice 1 : Classer ces quatre entrepôts (A, B, C et D) en fonction de leur utilisation de l'espace (dans lequel pourriez-vous rajouter le plus d'étagères ?) :

(rajouter le plus) 1 _____
2 _____
3 _____
(rajouter le moins) 4 _____

Exercice 2 : Classer ces quatre entrepôts en fonction de leur rapidité de navigation (lequel met le moins de temps pour ramener, une par une, les palettes 1, 2, 3 et 4?).

Vous pouvez dessiner le chemin suivi par le chariot élévateur sur les plans:

(moins de temps) 1 _____
2 _____
3 _____
(plus de temps) 4 _____

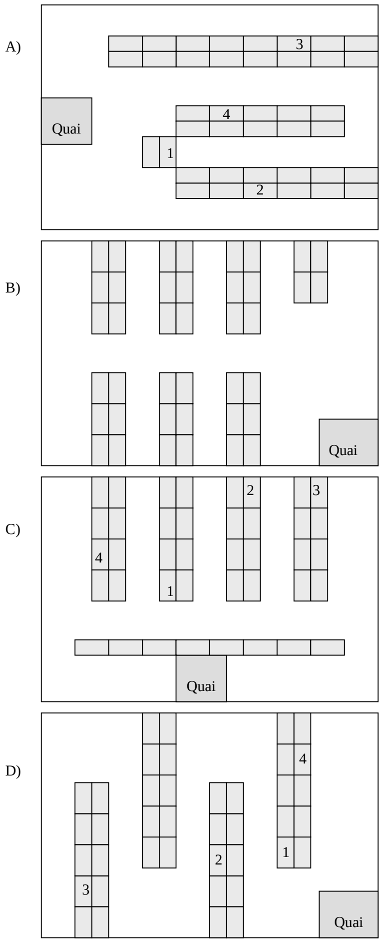
Exercice 3 : Pour **gagner de la place** dans un entrepôt il faut (cochez ce qui convient, plusieurs réponses possibles):
___ des allées courtes
___ des allées étroites
___ des allées longues
___ des allées larges

Pour **gagner du temps** dans un entrepôt, il faut :
___ des allées courtes
___ des allées étroites
___ des allées longues
___ des allées larges

Exercice 4 : Si vous deviez choisir un de ces entrepôts comme lieu de travail, lequel vous plairait le plus ?

Le mieux : _____
Pourquoi : ________________________

A.1.2 Post-test



Voici quatre entrepôts A, B, C et D ; chacun contient le même nombre d'étagères (40) et dispose d'un quai de réception et d'expédition. Les numéros 1, 2, 3 et 4 sont quatre palettes à sortir de l'entrepôt.

Exercice 1 : Classer ces quatre entrepôts (A, B, C et D) en fonction de leur utilisation de l'espace (dans lequel pourriez-vous rajouter le plus d'étagères ?) :

(rajouter le plus) 1 _____
2 _____
3 _____
(rajouter le moins) 4 _____

Exercice 2 : Classer ces quatre entrepôts en fonction de leur rapidité de navigation (lequel met le moins de temps pour ramener, une par une, les palettes 1, 2, 3 et 4?).

Vous pouvez dessiner le chemin suivi par le chariot élévateur sur les plans:

(moins de temps) 1 _____
2 _____
3 _____
(plus de temps) 4 _____

Exercice 3 : Pour **gagner de la place** dans un entrepôt il faut (cochez ce qui convient):
___ des allées courtes
___ des allées étroites
___ des allées longues
___ des allées larges

Pour **gagner du temps** dans un entrepôt, il faut :
___ des allées courtes
___ des allées étroites
___ des allées longues
___ des allées larges

Exercice 4 : Si vous deviez choisir un de ces entrepôts comme lieu de travail, lequel vous plairait le plus ?

Le mieux : _____
Pourquoi : ________________________

A.1.3 Final questionnaire

Questionnaire

Paire n°

Participant n°

Questions générales

Sexe : Homme / femme

âge : ......

Année au CPNV : 1ère / 2ème

Aviez-vous déjà utilisé la table avant aujourd'hui? Oui O | Non O

Questions concernant l'exercice

A quel point l'entrepôt que vous avez dû construire ressemble à l'endroit où vous travaillez?

pas du tout O | un peu O | moyennement O | assez O | beaucoup O

Travaillez-vous avec des palettes sur votre lieu de travail? Oui O | Non O

Travaillez-vous avec des étagères sur votre lieu de travail? Oui O | Non O

Travaillez-vous avec un Gerber sur votre lieu de travail? Oui O | Non O

Selon vous, quel était la surface totale de l'entrepôt en sachant qu'il a été réduit 50 fois?

.... m^2

Selon vous, quel autre chariot élévateur serait adapté à votre entrepôt?

....

Pendant la construction, avez-vous favorisé l'efficacité de l'entrepôt ou la place disponible?

....

Pendant la simulation, imaginons qu'un chariot élévateur passe plus de temps devant une étagère pour saisir une palette. Selon vous, est-ce possible dans la réalité? Si oui, quel en serait la cause?

....

Questions sur votre appréciation de l'exercice

	Pas du tout d'accord		Moyennement d'accord		Complétement d'accord
Je suis doué pour organiser un entrepôt	1	2	3	4	5
Je pense connaître les bonnes façons de construire un entrepôt	1	2	3	4	5
J'en connais moins que la plupart des gens sur la façon	1	2	3	4	5
Cet exercice représentait un défi pour moi	1	2	3	4	5
Cet exercice était représentatif de mes capacités	1	2	3	4	5
Mes capacités étaient tout juste suffisantes pour bien réussir cet exercice	1	2	3	4	5
Je n'ai pas eu besoin de beaucoup de créativité pour réussir cet exercice	1	2	3	4	5
Je me suis senti(e) libre pour construire cet entrepôt	1	2	3	4	5
L'entrepôt que j'ai construit n'est pas très original	1	2	3	4	5
Construire cet entrepôt n'était pas très intuitif	1	2	3	4	5
J'ai pensé à d'autres choses sans rapport pendant cet exercice	1	2	3	4	5
J'étais totalement concentré sur cette tâche	1	2	3	4	5

	Pas du tout d'accord		Moyennement d'accord		Compléte ment d'accord
J'ai oublié l'environnement qui m'entourait pendant la tâche (p.ex. la présence de l'expérimentateur)	1	2	3	4	5
J'avais l'impression d'être en face d'un vrai entrepôt	1	2	3	4	5
Je me sentais excité pendant la tâche	1	2	3	4	5
j'étais calme pendant que je construisais mon entrepôt	1	2	3	4	5
J'avais l'impression d'être passif pendant la tâche	1	2	3	4	5
J'étais content de faire cet exercice	1	2	3	4	5
Je me sentais irritable pendant cet exercice	1	2	3	4	5
J'ai essayé d'expérimenter différentes choses pendant l'exercice	1	2	3	4	5
Cela m'a plu d'essayer différentes possibilités	1	2	3	4	5
Je me suis ennuyé pendant la tâche	1	2	3	4	5
Je me suis senti frustré pendant cet exercice	1	2	3	4	5

A.2 Study 9 documents

The documents distributed to apprentices during Study 9, described in Section 7.4.1, are reproduced over the next pages:

1. the pre-test of the morning phase;
2. the first post-test of the morning phase;
3. the second post-test of the morning phase;
4. the pre-test of the afternoon phase;
5. the post-test of the afternoon phase.

A.2.1 Morning phase: Pre-test

Pre-test mise-en-place

Date : ____________________ Nom : ___________________ Groupe : _________

(**+** veut dire « augmente », **-** veut dire « diminue », **=** veut dire « ne change pas »)

1) La surface brute de stockage d'un entrepôt c'est:

2) Comment calcule-t-on le degré d'utilisation des surfaces:

3) En général, si vous prenez un contrepoids à la place d'un mât rétractable, que se passe-t-il pour :

+	-	=	Nombre de palettes sorties en une heure
+	-	=	Longueur du chariot
+	-	=	Risque d'accidents
+	-	=	Largeur d'allée nécessaire pour travailler
+	-	=	Degré d'utilisation des surfaces
+	-	=	Surface nette de stockage
+	-	=	Vitesse de circulation
+	-	=	Surface nette de stockage
+	-	=	Surface brute de stockage
+	-	=	Surface brute
+	-	=	Distance moyenne des étagères jusqu'aux quais

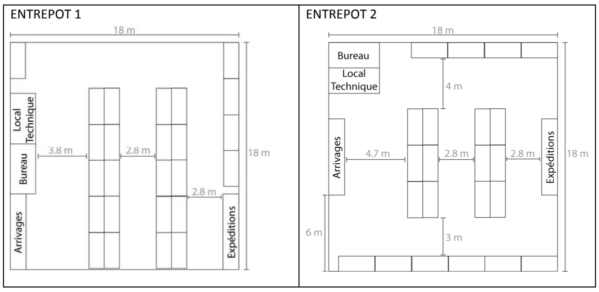
4) En général, si vous augmentez la largeur d'allée d'un entrepôt, que se passe-t-il pour

+	-	=	Surface nette de stockage
+	-	=	Surface brute de stockage
+	-	=	Nombre d'étagères dans l'entrepôt
+	-	=	Place à disposition pour circuler
+	-	=	Degré d'utilisation des surfaces

Pre-test mise-en-place

5) Si vous agrandissez le bureau dans votre entrepôt sans devoir enlever des étagères, que se passe-t-il pour :

+	-	=	La surface nette de stockage
+	-	=	Surface brute de stockage
+	-	=	Place à disposition pour mettre des étagères
+	-	=	Place à disposition pour circuler
+	-	=	Degré d'utilisation des surfaces



6) Que peut-on dire de l'entrepôt 2 par rapport à l'entrepôt 1 :

+	-	=	Distance moyenne au quai d'expédition
+	-	=	La surface nette de stockage
+	-	=	Surface brute de stockage
+	-	=	Place à disposition pour mettre des étagères
+	-	=	Place à disposition pour circuler
+	-	=	Degré d'utilisation des surfaces

7) Biffez entre 1-5 étagères dans l'entrepôt 1 pour diminuer la distance moyenne au quai d'expédition.

A.2.2 Morning phase: Post-test 1

Post-test 1 mise-en-place

Date : ____________________ Nom : ___________________ Groupe : _________

(**+** veut dire « augmente », **-** veut dire « diminue », **=** veut dire « ne change pas »)

1) La surface nette de stockage d'un entrepôt c'est:

2) Comment calcule-t-on le degré d'utilisation des surfaces:

3) En général, si vous prenez un gerbeur à la place d'un mât rétractable, que se passe-t-il pour :

+	-	=	Nombre de palettes sorties en une heure
+	-	=	Longueur du chariot
+	-	=	Risque d'accidents
+	-	=	Largeur d'allée nécessaire pour travailler
+	-	=	Degré d'utilisation des surfaces
+	-	=	Surface nette de stockage
+	-	=	Vitesse de circulation
+	-	=	Surface nette de stockage
+	-	=	Surface brute de stockage
+	-	=	Surface brute
+	-	=	Distance moyenne des étagères jusqu'aux quais

4) En général, si vous ajoutez des étagères dans un entrepôt, que se passe-t-il pour :

+	-	=	La surface nette de stockage
+	-	=	Surface brute de stockage
+	-	=	Place à disposition pour mettre des étagères
+	-	=	Place à disposition pour circuler
+	-	=	Degré d'utilisation des surfaces

Post-test 1 mise-en-place

5) Si vous diminuez la taille du local technique dans votre entrepôt sans ajouter des étagères, que se passe-t-il pour :

+	-	=	La surface nette de stockage
+	-	=	Surface brute de stockage
+	-	=	Place à disposition pour mettre des étagères
+	-	=	Place à disposition pour circuler
+	-	=	Degré d'utilisation des surfaces

6) Dessinez ci-dessous un entrepôt qui a les caractéristiques suivantes (1 étagère fait $3m^2$):

- Surface brute : 200 m^2
- Surface brute de stockage : 150 m^2
- Degré d'utilisation des surfaces : 10 %

A.2.3 Morning phase: Post-test 2

Post-test 2 mise-en-place

Date : ____________________ Nom : ___________________ Groupe : _________

(**+** veut dire « augmente », **-** veut dire « diminue », **=** veut dire « ne change pas »)

1) La surface brute de stockage d'un entrepôt c'est:

2) Comment calcule-t-on le degré d'utilisation des surfaces:

3) En général, si vous prenez un gerbeur à la place d'un mât rétractable, que se passe-t-il pour :

+	-	=	Nombre de palettes sorties en une heure
+	-	=	Longueur du chariot
+	-	=	Risque d'accidents
+	-	=	Largeur d'allée nécessaire pour travailler
+	-	=	Degré d'utilisation des surfaces
+	-	=	Surface nette de stockage
+	-	=	Vitesse de circulation
+	-	=	Surface nette de stockage
+	-	=	Surface brute de stockage
+	-	=	Surface brute
+	-	=	Distance moyenne des étagères jusqu'aux quais

4) En général, si vous augmentez la largeur d'allée d'un entrepôt, que se passe-t-il pour :

+	-	=	La surface nette de stockage
+	-	=	Surface brute de stockage
+	-	=	Nombre d'étagères dans l'entrepôt
+	-	=	Place à disposition pour circuler
+	-	=	Degré d'utilisation des surfaces

Post-test 2 mise-en-place

5) Si vous diminuez la taille du local technique dans votre entrepôt sans ajouter des étagères, que se passe-t-il pour :

+	-	=	La surface nette de stockage
+	-	=	Surface brute de stockage
+	-	=	Place à disposition pour mettre des étagères
+	-	=	Place à disposition pour circuler
+	-	=	Degré d'utilisation des surfaces

6) Dessinez ci-dessous un entrepôt qui a les caractéristiques suivantes (1 étagère fait $3m^2$):

- Surface brute : 250 m^2
- Surface brute de stockage : 180 m^2
- Degré d'utilisation des surfaces : 10 %

A.2.4 Afternoon phase: Pre-test

Pre-test Gestion de stock

Date : ____________________ Nom : ___________________ Groupe : _________

(**+** veut dire « augmente », **-** veut dire « diminue », **=** veut dire « ne change pas »)

Abréviations :

Q	= quantité commandée
Qopt	= quantité optimale de commande
B	= coûts de passation de commande
L	= coûts de stockage (en % de la valeur de l'article)
P	= prix par article

1) La formule d'Andler sert à calculer :

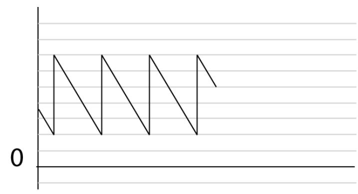
2) Le stock point de commande, c'est :

3) Les coûts de commande, c'est :

4) En général, si les besoins annuels pour un article augmentent, que devriez-vous modifier :

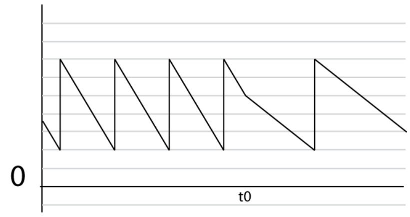
+	-	=	La quantité commandée
+	-	=	Le stock point de commande
+	-	=	Le stock de sécurité

La courbe ci-dessous montre le niveau de stock.
Montrez l'effet de ce changement sur cette courbe en la prolongeant :

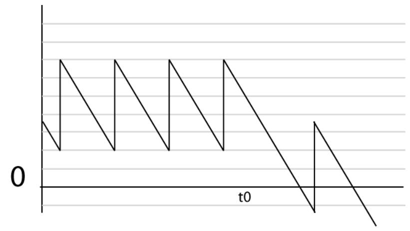


Pre-test Gestion de stock

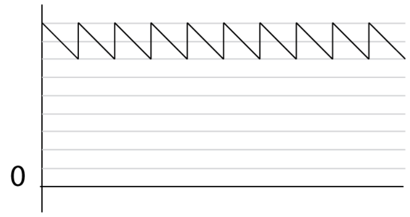
5) Observez la courbe ci-dessous. Que c'est-il passé au moment t0 ?



6) Observez la courbe ci-dessous. Que c'est-il passé au moment t0 ?



7) Que pensez vous de cette courbe ? Est-ce une gestion de stock efficace ? Pourquoi ?



A.2.5 Afternoon phase: Post-test

Post-test gestion de stock

Date : ____________________ Nom : ___________________ Groupe : _________

(**+** veut dire « augmente », **-** veut dire « diminue », **=** veut dire « ne change pas »)

Abréviations :

Q	= quantité commandée
Qopt	= quantité optimale de commande
B	= coûts de passation de commande
L	= coûts de stockage (en % de la valeur de l'article)
P	= prix par article

1) Pour calculer la quantité optimale de commande, j'utilise :

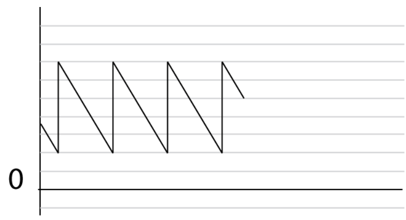
2) Le coût de passation de commande, c'est :

3) Les coûts de stockage, c'est :

4) En général, si le temps de réapprovisionnement pour un article augmente, que devriez-vous modifier :

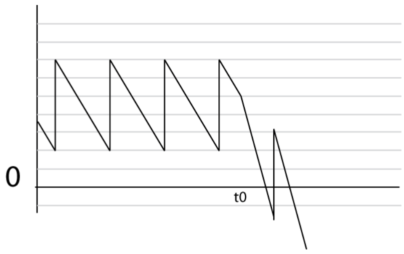
+	-	=	La quantité commandée
+	-	=	Le stock point de commande
+	-	=	Le stock de sécurité

La courbe ci-dessous montre le niveau de stock.
Montrez l'effet de ce changement sur cette courbe en la prolongeant :

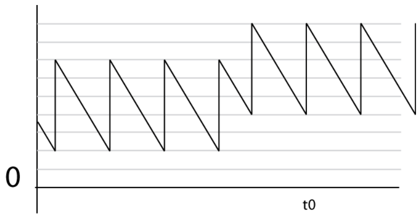


Post-test gestion de stock

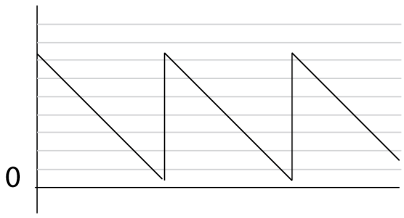
5) Observez la courbe ci-dessous. Que c'est-il passé au moment t0 ?



6) Observez la courbe ci-dessous. Que c'est-il passé au moment t0 ?



7) Que pensez vous de cette courbe ? Est-ce une gestion de stock efficace ? Pourquoi ?



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List of Acronyms

AR	Augmented Reality
CRC	Cyclic Redundancy Check
CPNV	Centre Professionel du Nord Vaudois
CSCL	Computer-Supported Collaborative Learning
DBR	Design-based Research
DM	Direct Manipulation
DOF	Degree of Freedom
EPFL	Ecole Polytechnique Fédérale de Lausanne
FEC	Forward Error Correction
GUI	Graphical User Interface
HCI	Human-Computer Interaction
IPF	Interactive Paper Form
MER	Multiple External Representation
OoI	Object of Interest
PUI	Paper User Interface
TEL	Technology-Enhanced Learning
TaPE	Tangible and Paper Environment
TUI	Tangible User Interface
UbiComp	Ubiquitous Computing
WIMP	Windows-Icon-Menu-Pointing device

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Education

2006–2010	**PhD in Computer Science**, *École Polytechnique Fédérale*, Lausanne. The Complementarity of Tangible and Paper Interfaces in Tabletop Environments for Collaborative Learning.
2000–2005	**Master in Computer Science**, *École Polytechnique Fédérale*, Lausanne, Master project: Neural implementation of a Hidden Markov Model for spatial localization using continuous 2D visual inputs.
2002-2003	**Erasmus exchange**, *Universidad Politécnica de Madrid*, Madrid.
1995-2000	**Maturité cantonale**, *Lycée-collège des Creusets*, Sion, Orientation scientifique.

Languages

French	**Native speaker**	
English	**Advanced**	*Fluent in writing and speaking. Daily use.*
German	**Advanced**	*Fluent in speaking. Daily use.*
Spanish	**Average**	*Average reading and writing skills.*

Work Experience

Assistantships

2007-08	**Assistant**, *Information Technology Project*. First year Java programming project: lab session support, exam preparation and supervision.

Internships

2005-06 (6 months)	**IT trainee**, *Novelis Switzerland SA*, Sierre. Evaluation and selection of a desktop software management solution.
2005 (2 months)	**Research Assistant**, *Cellular Architectures Research Group (EPFL)*, Lausanne.
2004 (2 months)	**R&D trainee**, *SportAccess SA*, Sion. Evaluation and development of copy protection solution
2001-03 (5 months)	**Student job**, *Centre de Recherche en Environnement Alpin*, Sion.

Publications

Conference Papers

2010 Enrico Costanza, Jacques Panchard, Guillaume Zufferey, Julien Nembrini, Julien Freudiger, Jeffrey Huang & Jean-Pierre Hubaux. *SensorTune: a Mobile Auditory Interface for DIY Wireless Sensor Networks*. In Proceedings of the 28th International Conference on Human Factors in Computing Systems (CHI 2010), pages 2317–2326, Atlanta, April, 2010.

Aurélien Lucchi, Patrick Jermann, Guillaume Zufferey & Pierre Dillenbourg. *An empirical evaluation of touch and tangible interfaces for tabletop displays*. In Proceedings of the Fourth International Conference on Tangible, Embedded, and Embodied Interaction (TEI 2010), pages 177–184, Cambridge (Massachusetts), January, 2010

2009 Guillaume Zufferey, Patrick Jermann, Son Do Lenh & Pierre Dillenbourg. *Using Augmentations as Bridges from Concrete to Abstract Representations*. In Proceedings of the 23rd British HCI Group Annual Conference on HCI 2009: Celebrating People and Technology (British HCI 2009), pages 130–139, Cambridge (UK), September, 2009.

Guillaume Zufferey, Patrick Jermann, Aurélien Lucchi & Pierre Dillenbourg. *TinkerSheets: Using Paper Forms to Control and Visualize Tangible Simulations*. In Proceedings of the Third International Conference on Embedded and Tangible Interaction (TEI 2009), pages 377–384, Cambridge (UK), Februar, 2009.

2008 Patrick Jermann, Guillaume Zufferey & Pierre Dillenbourg. *Tinkering or Sketching: Apprentices' Use of Tangibles and Drawings to Solve Design Problems*. In Times of Convergence. Technologies Across Learning Contexts (ECTEL 2008), pages 167–178, Maastricht, September, 2008.

Guillaume Zufferey, Patrick Jermann & Pierre Dillenbourg. *A Tabletop Learning Environment for Logistics Assistants: Activating Teachers*. In Proceedings of the Third IASTED International Conference Human-Computer Interaction (IASTED-HCI 2008), pages 37–42, Innsbruck, March, 2008.

2006 Pierre-André Mudry, Guillaume Zufferey & Gianluca Tempesti. *A dynamically constrained genetic algorithm for hardware-software partitioning*. In Proceedings of the 8th annual Conference on Genetic and Evolutionary Computation (GECCO'06), pages 769–776, Seattle, July, 2006.

Gianluca Tempesti, Pierre-André Mudry & Guillaume Zufferey. *Hardware/software coevolution of genome programs and cellular processors*. In Proceedings of the 1st NASA/ESA Conference on Adaptive Hardware and Systems (AHS'06), pages 129–136, Istanbul, June, 2006.

Pierre-André Mudry, Guillaume Zufferey & Gianluca Tempesti. *A hybrid genetic algorithm for constrained hardware-software partitioning*. In Proceedings of the 2006 IEEE Workshop on Design and Diagnostics of Electronic Circuits and Systems (DDECS'06), pages 3–8, Prague, April, 2006.