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Integrating Physical and Virtual Knowledge Work Environments using Physical-Virtual Artefacts — A Proposal

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INTRODUCTION & MOTIVE

It is reasonable to believe that knowledge work (KW) will become an increasingly common occupation in the future [1]. Since computer artefacts via the invention of the personal computer in the mid-80's have become an important part of today's KW environments, and since they probably will have increased importance in future KW environments, one important HCI research area is the combined study of KW and how computer artefacts can support activities involved in KW.

The vision of ubiquitous computing [13] emerging in the beginning of the 1990's and the development of various HCI technologies that explicitly try to utilize different senso-motoric human capabilities in recent years, for instance [4, 6], can very well be seen as the beginning of a change of direction regarding design of environments for knowledge workers. However, good general design tools to support analysis and development of these new artefacts are still lacking. The work presented in this paper is an initial approach to study these new artefacts from a theoretical design perspective.

What we are facing is a tighter coupling between physical and virtual artefacts as well as a higher degree of freedom to choose how 'physically' or how 'virtually' we want to work, depending on task and geographical position, as well as upon personal preferences like working style or current mood.

Knowledge workers have to keep track of information entities, tools and agents in both physical and virtual environments, a task which today can be both time-consuming and distracting. In this paper we propose a unifying view that hopefully can encourage the development and design of artefacts that to a high degree could be used and/or would be present in *both* physical and virtual environments (see Figure 1).

The Physical Environment is Here to Stay

Although people increasingly use IT in both traditional and more modern activities because of the efficiency benefits of virtual environments in many

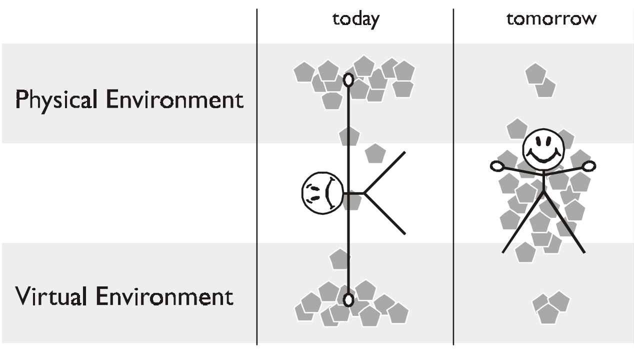

Figure 1: *Vision and goal: Artefacts that are both physical and virtual at the same time.*

situations, the physical environment has yet been difficult to replace entirely. Besides the large number of social and cultural reasons for this 'inertia', technology has in many cases not been able to support cognitive and perceptual constraints and abilities of humans as well as the physical environment does. For instance, the paperless society which was forecasted and acknowledged by many people some decades ago has not become a reality at least partly because of the flexibility and ergonomic superiority of traditional paper in comparison to screen-based publications [10]. Also, to provide multiple physical interaction devices instead of just one or two (mouse and keyboard) shows promising results [3] inspiring to explore the physical environment as a user interface further.

The trend in industry with shorter product development times, the emergence of highly portable computer power and wireless networks will enable and force many knowledge workers that previously had limited contact with the physical reality affected by their work to do much of their work out there. This narrowing of distance is a two-way process so the people who earlier worked in the field, involving only small elements of knowledge work, will soon have technological support and educational skill enough to make necessary decisions themselves on the fly. Knowledge work and physical action will become increasingly intertwined. For example, in modern forest industry, logging is done using mobile machines equipped with computers wirelessly connected to a central server keeping track of current prices on different wood types, suggesting to the machine and the knowledge worker operating it to cut the trees that are currently most profitable. The education and experience needed to successfully drive these machines involves many knowledge areas like forest ecology, computer technology, mechanics and economy.

In this paper we will assume that in the foreseeable future, people will continue to perform many activities in the physical environment, and we will try to shed some light on why people might prefer a certain environment (physical or virtual) when performing specific knowledge work tasks. We believe that to view the two environments and the artefacts they encompass as one single environment can inspire and help designers to bridge the gap and create better working environments for knowledge workers.

PHYSICAL AND VIRTUAL ENVIRONMENTS

As indicated earlier, this paper is based on the hypothesis that knowledge workers perform their work mainly in two environments. The *physical environment* is the environment in which the knowledge worker performs activities relying on physical actions. Any traditional personal computer (PC) is viewed as any other physical object and what might be happening on the computer screen is excluded from the physical environment. An example would be an ordinary office, but our definition does not rule out more temporary physical environments like conference halls, meeting rooms, trains or aeroplanes. The *virtual environment* denotes the environment in which the knowledge worker *relies* on computer power in order to perform the specific knowledge work activity. An ordinary PC running some operating system can, for example, provide this environment.

Both environments present unique affordances and constraints [9] to the knowledge worker acting in the environment as well as to the different artefacts present within them. Having knowledge work as our major interest, we can identify some characteristics distinguishing the two environments from each other (Table 1).

Environment	Physical	Virtual
perceptual feedback (tactile, visual, auditive)	very high	low
social interaction support	very high	low
independency on physical location	low	high
support for distribution of artefacts (sending, copying, publishing)	low	very high
symbolic manipulation support	low	very high
support for reversible operations (UNDO)	low	high

Table 1: *Some characteristics of physical and virtual environments.*

This list presents some general environmental characteristics and is by no means complete or always applicable. Also, continuous research and development tend to decrease some of the differences. For instance improved interaction technologies based on immersive Virtual Reality (VR) might increase perceptual feedback in virtual environments. In spite of the many differences, of which some are mentioned above, there are in general a lot of similarities in both functionality and appearance between the environments. One of the reasons can be that virtual environment designers often are encouraged explicitly and implicitly to make use of metaphors based on affordances and constraints present in the physical environment, when designing virtual functionality.

The Physical-Virtual Environment Gap

Traditionally, knowledge workplaces equipped with personal computers tend to create a significant gap between the virtual environment offered by the computer system on the one hand, and the surrounding physical environment on the other. This environment gap makes it costly to, (1) transfer information (e.g. documents) between the two environments, and (2) to maintain a coherent cognitive model of the physical-virtual knowledge work environment, since connections between equivalent artefacts in the two environments are rather weak.

Of course, the cost is in this context a relative measure. In this paper we will relate the costs to (1) how much of a 'productivity bottleneck' the cost for performing the specific activity is, in comparison to other knowledge work tasks, as well as (2) what today's and soon-to-come technology can or should be able to offer the knowledge worker in order to minimise them.

The origin of the environment gap can easily be traced historically. From the virtual side, PCs and PC operating systems originate from mainframe-terminal systems not designed for knowledge work as it is present today [8]. These systems were designed for more or less pure symbol manipulation with very slow interactions between the system, the user, and the physical world (e.g. sales calculation, printing of order lists, the control of industrial processes). In contrast, modern knowledge work involves short interaction cycles and complex communication patterns. From the physical side, knowledge work is heavily connected to culture and conventions in traditional offices, as storing, retrieving and writing paper documents was, and still is, a major occupation. However, as will be discussed more thoroughly below, modern knowledge work activities involve new twists of the old tasks that the two environments were originally designed to support. We argue that these new tasks are best supported by artefacts that are deliberately designed for work in both environments.

Cognitive Costs for Handling Incoherence Between the Environments

In order to perform work, the knowledge worker has to build and maintain a mental model of the working environment, its contents, and the task. Two factors making this difficult in today's knowledge work environments are:

- metaphoric incoherence — Equivalent physical and virtual artefacts in the environment differ in behaviour and appearance even if their basic characteristics are the same (e.g. the virtual paper basket behaviour and appearance is different from the physical), creating a metaphorical incoherence only to be overcome by the actor's cognitive effort [9].
- identity incoherence — The connection between equivalent artefacts in the physical and virtual environments are weak (e.g. hand-written changes to a physical text document does not affect the equivalent virtual document), forcing the knowledge worker to construct and maintain the current state of the working environment, raising questions like: "In which environment do I have the latest version of this specific document?" etc.

INFORMATION ENTITIES

To concretise and exemplify the problems and obstacles that the physical-virtual environment gap can give rise to, we will now focus on knowledge work tasks that involve one important artefact category: information entities.

Definition: An *information entity* is an artefact whose main purpose is to carry information in order to facilitate knowledge work tasks like perception, transformation, and sharing of information among knowledge workers.

Examples: Text documents, sketches, pieces of music.

Important Task for Knowledge Workers — Trading and Exchanging Information Entities

Knowledge workers are people that acquire knowledge and disseminate virtual or physical information entities that can, under suitable circumstances, be used by other knowledge workers to gain knowledge via a learning process. Internal results of 'pure' KW is knowledge like the understanding of concepts, reflective thoughts and awakening intentions in the mind of the knowledge worker. At will, this knowledge can be implemented in other virtual or physical information entities (knowledge work products) that informs[1] other recipients, using simple or combinations of modalities like speech, sound, text, picture, animation, physical shape etc. This external product can be of a relatively simple construction intuitively understood by the recipient, but can also be of a more complex nature in the sense that it has to be thoroughly examined to be completely understood. The latter happens most evidently when the framework in which the entity was developed is novel to the spe-

1. We us the term 'inform' in the meaning coined by Kidd [7].

cific recipient, demanding further knowledge work and learning.[1]

Costs for Transferring Information Entities between the Environments

Transfer costs for overcoming the physical-virtual environment gap can take many shapes, for example:

- time — The task to transfer the information entity between the environments is a time-consuming process for the knowledge worker.
- cognitive effort — The complexity of bridging the gap demands considerable cognitive work, distracting the knowledge worker from more creative knowledge work activities.
- money — The equipment or manpower needed to perform the environment-bridging task is expensive.

To exemplify the cost factors outlined above, let us consider a text document. Having it in a word processor makes it easy to transfer (actually to copy) from the virtual environment to the physical by the use of a printer. However, although it would be very useful sometimes to reverse this process, it is a more complex activity. Especially if we want to regenerate the specific features of the original *virtual* information entity and the affordances of the virtual environment (for instance to have the document in a word processor environment). The reason for this is the considerable (meta-) information loss present when transferring the artefact between the two environments.

So, Why Not Simply Stick to One of the Environments?

If transferring information entities between physical and virtual environments often is difficult, why do knowledge workers bother doing it? This question is similar to "What are computers good for?" but viewed from a slightly different angle. The answer is that each of the two environments connect unique information attributes and sensory characteristics to artefacts. Tools and mechanisms within the environments utilize these environment-specific artefact features to provide functionality and sensuality towards the knowledge worker that can only be realised in the specific environment. The knowledge worker can choose the environment that best suits the current knowledge work task. This decision is analogous to how tools are chosen *within* the environments.

1. In fact, the complexity of products have dramatically increased since the beginning of the industrial revolution, and there is no reason to believe that this will change in the future information-dense society [1].

The Meaning of Transferring Artefacts between Physical and Virtual Environments

Because the physical and virtual environments are based on two different (but of course related) kinds of elementary particles[2] (atoms respectively bits), it is in some sense impossible to transfer literally a physical artefact from the physical environment to the virtual environment, or vice versa. However, on a higher conceptual level it can be useful to regard certain processes involving both environments as a kind of artefact transfer. We can then view the physical and the virtual artefacts as two different *instantiations* of an abstract artefact. This is especially true for artefacts like information entities whose main purpose is to encompass information to be shared among knowledge workers.

The Fundamental Design Error to Forget About the Physical-Virtual Environment Cycle

Current design of information entity embodiment present in physical-virtual environments does not seem to consider the fact that knowledge workers perform their work in both environments and that there is no final destination environment for information entities. In fact, in many kinds of knowledge work situations, the destination is the physical-virtual environment and *not* one or the other. You never know how your information entity will be used (or re-used), and parts or the whole entity might travel back and forth between the environments many times while it is used by other knowledge workers.

PHYSICAL-VIRTUAL INFORMATION ENTITIES

To encourage the design of information entities that are easy to handle, no matter what environment the knowledge worker might choose for the moment, we can define some necessary attributes:

Definition: A *physical-virtual information entity* is an abstract information entity that (1) is instantiated in both the physical and virtual environment, where (2) these instantiations to a large extent utilize the unique affordances and constraints that the two different environments facilitate, and finally (3) where one instantiation of a specific physical-virtual information entity is easily identified if an equivalent instantiation in the other environment is known.

Not all information entities fall into this category. For instance, in contrast to a printed text document, a hand-written note for a paper slip usually doesn't exist in a virtual environment and it can only with high costs be transferred to the virtual environment in

2. We can choose to see bits as elementary particles because they are the smallest possible entities in the virtual environment.

such a way that it makes use of facilities in the virtual environment like for instance automated free-text search etc. Therefore the hand-written note does not qualify as a physical-virtual information entity, according to the definition above.

True Physical-Virtual Information Entities Survive a Gap-Cycle Without Actor Intervention

Consider a text document produced in a virtual environment and which is copied into the physical environment by using the interfacing technology called printer. Anyone who gets hold of this paper document might want to make changes to the document and/or reuse parts of it in her/his own work activities, and/or store it in a personal digital library for easy retrieval at a later stage. In other words, the user of the paper document would like to have access to a virtual version of the paper, linked to the physical one. As pointed out earlier, this is usually not easy to achieve today. However, although standards are still missing, technology for solving this problem is on its way, taking two directions:

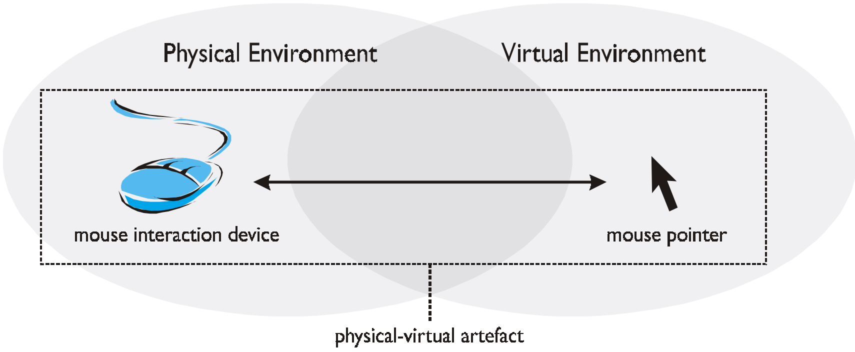

Figure 2: *A physical-virtual artefact and its' two instantiations.*

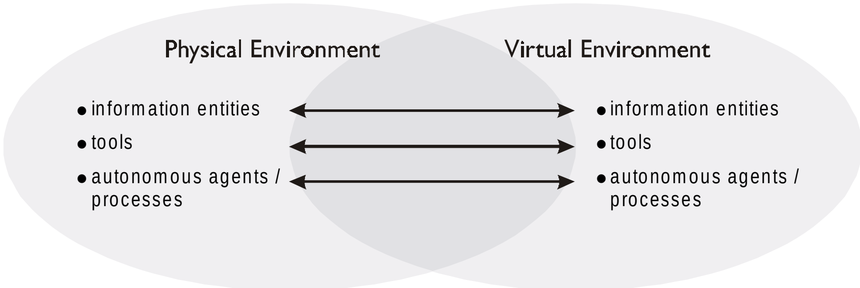

Figure 3: *Three categories of physical-virtual artefacts in knowledge work environments.*

(1) The paper has a bar code/magnetic strip or any other digital unique identifier attached to it readable by virtual environment interfacing technology like a bar-code pen, and which immediately brings forward the authors original virtual version of the document (digitally watermarked so that the origin of the document can be traced to the original author) from a large DL like the World-Wide Web. A slightly more general approach is the 'Passage-Bridge' solution in [12, p.17].

Or, (2) the paper has a digital media of some kind attached to it (magnetic, optic, holographic) that actually contains a virtual version of the paper, ready to be downloaded from the paper itself to the actors personal virtual environment. Considering the decrease in cost and size of digital memories, this solution will probably soon be possible.

In any of these two cases, the specific text document is regarded to be a true physical-virtual information entity since to transfer it (or a copy of it) back and forth between the two environments does not imply any loss of information. Although not all information contained in the entity can be used in one of the specific environments, it is still directly or indirectly attached to the entity ready to be utilized in the other environment at will.

PHYSICAL-VIRTUAL ARTEFACTS

As explained in the introduction section, our vision is to create an environment for knowledge work in which as many artefacts as possible support activities in both environments (see Figure 1 on page 1). In order to widen the physical-virtual perspective from the information entities discussed in the previous section, we can simply generalise the definition to concern artefacts in general:

Definition: A *physical-virtual artefact* is an abstract artefact that (1) is instantiated in both the physical and virtual environment, where (2) these instantiations to a large extent utilize the unique affordances and constraints that the two different environments facilitate, and finally (3) where one instantiation of a specific physical-virtual artefact is easily identified if an equivalent instantiation in the other environment is known.

How to make 1 + 1 = 1

As mentioned earlier, the two environments afford and constraint the design of artefacts in different ways and give certain characteristics to the physical instantiation of a specific artefact (for instance this text document in paper form), and certain other characteristics to the virtual instantiation (this document in a word processor environment). Nevertheless, they are for most purposes conceptually one and the same artefact in the mind of the user. It can therefore be appropriate to regard the two instantiations as one single unit, i.e. a physical-virtual artefact.

In order to give the knowledge worker a uniform conception of the physical-virtual artefact, we believe that it is more important to create a tight coupling between the instantiations, as required by part 3 of the definition, rather than to give them similar perceptual appearances. This is because to fully take advantage of the unique affordances and constraints in the environments (as required by part 2 of the definition) the instantiations most probably *have* to differ in appearance and functionality. Thus, artefact designers must, to some extent, renounce the use of similarity metaphors and instead increasingly afford a uniform view of the artefact by other means, e.g. by maintaining a tight coupling between its instantiations. The instantiations should complement each other rather than look the same.

An example of a physical-virtual artefact with tight-coupled instantiations is the ‘mouse interaction device <-> mouse cursor’ artefact (see Figure 2) used to interact with popular windows-based virtual environments. The physical instantiation is shaped according to fit the human hand while the virtual instantiation is designed to not take up too much space, be visible on top of any kind of background and to have a distinct ‘action point’. The instantiations complement each other in functionality and because of the tight coupling, the user tend to identify them as one artefact.

Another example of a physical-virtual artefact would be compact disc (CD) players mounted in PCs. Users insert and remove music media in the physical environment but control the playing process (track number, volume etc.) in the virtual environment. Some of these CD players have a physical playing interface as well, allowing users to choose freely in which environment to interact. Contrary to the mouse artefact, virtual instantiations are usually designed based on the appearance of the physical instantiation. The tight coupling between the instantiations is however as strong as in the mouse example.

Physical-Virtual Artefacts in Knowledge Work Environments

The definition of physical-virtual artefacts is not intended simply to divide artefacts within knowledge work environments into two distinct sets (physical-virtual and not physical-virtual). Instead, we believe that it can be interesting to view also artefacts not perfectly satisfying the definition, from a physical-virtual perspective. The definition should be treated as a combined attribute that artefacts can comply with to a smaller or larger degree.

A simple categorisation of common artefacts in knowledge work environments can be to make distinctions between *information entities*, *tools* and *autonomous agents/processes* (see Figure 3). The three artefact categories will briefly be presented below:

- information entities — Artefacts whose main purpose is to encompass information in such a way that they facilitate knowledge work tasks like transformation, perception, and sharing of information among knowledge workers.
- tools — Artefacts helping the user to perform knowledge work tasks, for instance retrieving, analysing, organising, transforming and disseminating information entities efficiently. The tools are more or less directly controlled and supervised by the knowledge worker her/himself.
- autonomous agents/processes — Artefacts or humans that take care of complex tasks including decision-making with small intervention needed from the knowledge worker. The tasks performed by these agents are typically of a continuous nature, never to be completely finished.

FUTURE SCENARIO & ANALYSIS

To get a notion for how a future knowledge work environment might look like and what kind of physical-virtual artefacts it might contain, we can use ideas from some recent research prototypes, some of the criticism on current information entity design discussed in this paper and spice it with some imagination. The scenario will be followed by an analysis done from a physical-virtual artefact perspective.

The Virtual Environment Embedded In the Physical

Consider a knowledge worker’s office a few years from now. The walls are covered by bookshelves and posters, very much the same as in many offices today, but the areas not covered by furniture and other physical artefacts are instead used as virtual areas onto which the virtual environment is visually projected as in Liveboard [2] and more recent prototypes. This allows the user to arrange the virtual environment similar to the physical environment. The large size of the total screen area allows the knowledge worker to overview many applications and virtual artefacts without having to switch between them like in traditional windows-based small-screen environments. Since the virtual environment really covers *all* empty wall areas, it also increases the possibility to put virtual instantiations of physical-virtual artefacts close to the equivalent physical instantiation, increasing the feeling of an integrated physical-virtual environment. For instance, the virtual and physical instantiations of a paper basket can be put close to each other.

There is also a desk and a chair, but the desk is, like the empty wall areas, a window into the virtual world, i.e. a DigitalDesk [14]. You can interact with the virtual environment using your fingers or a pen which is tracked within the room via a 3D positioning system; the computer system always knows the location of the pen as well as in which direction it is pointing. This allows the user to interact with the virtual areas remotely; a 'mouse' cursor is shown whenever the device is pointing into a virtual area. Moving virtual objects between different parts of the virtual area is done in a Pick and Drop [11] fashion.

The Physical-Virtual Mail Frog

On the desk, among some paper documents, we can find other artefacts. In one corner there is a physical-virtual mail box notifier. This particular knowledge worker has chosen one in the shape of a frog. It is connected to the e-mail box in the virtual environment as well as to the physical mail box located in another room. As soon as a letter arrives (virtual or physical), the frog jumps into the centre of the desk and croaks, in order to inform the knowledge worker about the new mail. If the knowledge worker is not responding, by voice or by tapping it on the head, it will soon jump back to its corner. If the knowledge worker prefers not to be disturbed, the frog can be covered by a blanket, which will keep the frog silent and still.

Letters to be sent virtually are edited on the desk using pen or keyboard and dragged to the position of the frog for delivery. Physical letters to be sent are also put close to the frog followed by a tap on the frog to signal that this letter should be sent. Whenever the knowledge worker is approaching the door, the frog will croak in a way to remind the knowledge worker to put the letter in the outgoing mail pile in the post room (or to collect incoming physical mail if there is such), in case she/he might pass it anyway.

Keeping Track of Physical-Virtual Information Entities

All paper documents in the office are tagged with unique digital IDs, since this is the way they come out from the printer these days. To identify a specific document it is enough to put it on the desk (where it will be automatically recognised) or to move the pen close to the document's tag which is always placed in the upper left corner of the first page.

The last operation also has the useful side-effect of also recognising the document's physical location in the room, since as mentioned before, the pen's location is always known by the system. Taking this further, it means that by regularly moving the pen around the office, the system will be informed about the positions of every single information entity (and other tagged artefacts) in the room. Thus, if the knowledge worker can't find a certain physical instantiation of a document, she/he can do an alphabetic search in the virtual environment and get the position visualised in a VR model of the office. Of course, this way of positioning artefacts is not always precise but it is a cheap and simple alternative compared to attaching location devices to everything.

The Physical-Virtual Paper Basket

The tagging of information entities makes it easier to create physical-virtual tools operating on them. When the knowledge worker puts a paper document in the paper basket, the paper basket can identify the document and consequently delete any equivalent virtual instantiation. The other direction is a bit more complicated but one simple solution is to let the system regard the physical instantiation as 'to be put in the paper basket' and whenever the user happens to cross the document with the pen, kindly ask the user to throw it away.

Analysis

- *The pen* is a physical-virtual tool with basically the same characteristics as a traditional mouse (see the previous section on physical-virtual artefacts) but with an extra space dimension.
- *The paper basket* is a physical-virtual tool that behaves similarly for physical and virtual instantiations of information entities thrown into it. However, incoherence problems occur when a virtual instantiation is thrown away because the system is not able to put the physical instantiation in the paper basket's physical instantiation, a problem which has been fixed with the ad-hoc solution of a 'garbage buffer'.
- *The frog* is a physical-virtual agent controlling physical-virtual mail flow. In order to get around the problem with the distant physical mail box, the designer has implemented a reminder function that is activated when there is physical mail to receive

or send and the knowledge worker leaves the room. The frog has one virtual instantiation, the e-mail box, and one distributed physical instantiation; the frog itself and the physical mail box.

- *The documents* have been discussed thoroughly earlier in the section on physical-virtual information entities and should need no further explanation.
- *The room* is a physical-virtual tool consisting of itself as the physical instantiation and the VR model, supporting free-text search and other typical virtual functionality, as the virtual instantiation.

Some Important Design Issues

Keeping the physical world predictable: As more and more physical-virtual artefacts appear in our everyday environment, can we with sufficient accuracy predict the outcome of our physical actions? What happens if a colleague enters your office and casually plays around with some seemingly 'harmless' artefacts which in fact causes your personal DL to become a chaos? Do we need identity checks for all actions?

Version handling of information entities: When should a change in an information entity affect all other copies of it and when should it not? A problem exemplified in the paper basket case in the scenario. How should old and new versions be handled?

Even if these questions are not new, the need for consistent design is as important as ever before.

SUMMARY

Based on problems caused by the physical-virtual information gap, we have defined some necessary attributes for physical-virtual information entities. These characteristics have been generalized to physical-virtual artifacts and the applicability of this view has been exemplified in a future scenario followed by an analysis.

RELATED WORK

As mentioned in the introduction, this work is to a large degree inspired by recent artefact research prototypes that in different ways and for different purposes try to utilize characteristics of the physical world in their design. However, to our knowledge, there is no unified design-theoretical approach that focuses on the physical-virtual environment integration from a *general* artefact perspective, such as the one presented.

FUTURE WORK

The general applicability of the physical-virtual viewpoint will be evaluated during field studies scheduled for autumn 1998, where knowledge workers in Swedish industry will be subjected to task analysis from a physical-virtual environment perspective. We intend to expand the list of characteristics (see Table 1 on page 2) for both environments and in this way construct an n-dimensional space where common knowledge work artefacts can be placed according to their dependency of environment characteristics. This space will serve as a guideline for development of new artefacts, helping designers to decide what functionality of the artefact should be put in the physical environment and what should be implemented in the virtual environment. If a desirable functionality is not possible to afford in the initial environment, maybe it can be realised in the other artefact instantiation?

Further, the relationships between artefact instantiations will be studied more thoroughly in order to define different kind of relationships between them (1-1, 1-many, uni- and bi-directionality etc.).

CONCLUSIONS

We believe that the unified physical-virtual perspective can be a useful tool for bridging the physical-virtual environment gap, helping designers to focus on the intended functionality of artefacts and breaking loose from traditional environment dependent design patterns. The physical-virtual perspective can be used for analysis, redesign and new development of artefacts intended to support knowledge work.

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