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A COMPARISON AND VALIDATION OF 13 CONTEXT META-MODELS

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Abstract

'Context' is a significant element in the field of context-aware and pervasive computing. Thereby, a context meta-model defines context on an abstract level. Simultaneously, a context meta-model builds the basis for specific context models that support system designers in their decisions which context variables to integrate in a particular intelligent context-adaptive system. This paper compares 13 meta-models with respect to their scope. Taking an empirical approach, we matched the meta-models against context variables used in research practice. On the one hand, the meta-models find themselves well reflected by research practice, in a sense that the models' context categories can be described by context variables reported in research. On the other hand, the results clearly indicate that each of the 13 context meta-models fails to describe the full landscape of context. Many context variables used in reported research are not covered by any of the analysed context meta-models. Accordingly, this paper calls on the research community to advance its basic theories continuously because the research field needs theories that reflect reality.

Keywords: Context meta-models, Model comparison, Pervasive computing, Context, Review.

1 Introduction

Already back in the 1990's researchers started to engage with context-aware computing (Schilit and Theimer, 1994). Since then, the community has grown rapidly. The vision is that technology is intelligently weaved into our everyday lives (Weiser, 1991) and systems adapt their behaviour according to the context they run in (e.g., Ferscha et al., 2002, Brown et al., 1997, Ferscha et al., 2004). In such pervasive computing environments, users frequently interact implicitly or indirectly with an intelligent system without having to be aware that they are using a system in the moment.

One significant element in the pervasive computing field is known as 'context'. The scale of definitions of context shows a broad spectrum. Early attempts to define the context resulted in enumerations of examples (e.g., Schilit and Theimer, 1994, Dey, 1998) or choosing synonyms for context (e.g., Brown et al., 1997). The basis for many definitions was provided by Dey and Abowd (2000), "context is any information that can be used to characterize the situation of an entity". This definition, though, is very broad and generic. Similarly, Soylu et al. (2009) point out that "context is an open concept since it is not limited with one's imagination". In contrast, other definitions are highly specific to a certain application (e.g., Müller and Krüger, 2009, Bauer and Spiekermann, 2011).

Due to the challenge to define context verbally in one sentence, researchers started to elaborate context meta-models using graphical notations. A context meta-model is a generic description of the context world on a meta-level that is not targeted towards a particular system. Furthermore, a context-meta model builds the basis for translating it into context models for specific context-adaptive systems, which finally guide system designers in determining which context variables to consider for a particular context-adaptive system. However, a scale of context meta-models exists and the community could not yet agree on a single one.

Against this background, the present paper provides an overview of existing context meta-models and compares them with respect to their comprehensiveness. Furthermore, we discuss how these context meta-models are reflected in the current research practice in the pervasive computing field.

The paper is structured as follows: First, the reader is introduced to the field of comparing models as well as context meta-models (Section 2, related work). Section 3 essentially describes the applied methods for comparison and validation. Then the paper presents the comparison of 13 context meta-models in detail (Section 4). In Section 5, the paper discusses the findings and interprets them, before the paper concludes with a summary and an outlook to future work (Section 6).

2 Related work

2.1 Approaches to compare models

The most basic characteristic of a model is that it is an abstraction of reality. Accordingly, each model represents reality with a varying level of completeness (Peuquet, 1984).

When comparing two models, the main task is to calculate the mappings and the differences between models (Lin et al., 2004). Comparing models at a high level of abstraction is challenging though (Kolovos et al., 2006). Manual comparison is tedious, time consuming, and prone to error. Accordingly the modelling community seeks for automation of model comparison and visualisation of the results (Lin et al., 2004).

Fundamental issues of model comparison – whether done manually or automatically – is what properties of models need to be compared and at which level to compare them (Lin et al., 2004). Having decided on these issues, Kolovos et al. (2006) suggest to compare models pairwise. First it is necessary to partition model elements into following categories: (1) elements for which matching elements exist in the opposite model and (2) elements for which matching elements do not exist in the opposite model. For matching elements, it is necessary to further judge the conformance match or mismatch between them (e.g., two elements may match in their names but one is declared as abstract while the other as concrete). For elements that do not have a matching counterpart in the opposite model, we differentiate between elements that are included in the domain of the comparison operation and those that are excluded. However, before being able to compare the elements, once has to set up rules that indicate whether two elements match and/or conform to each other. This issue, though, is specific to the models' domains, frameworks, and particular characteristics and cannot be answered from a general perspective.

2.2 Context meta-models

Although many people believe to understand the notion of 'context', they are rarely able to verbally express its meaning and are also not in a position to distinguish it clearly from non-context (Dey, 2001).

For the scope of this work, context is approached from a requirements engineering point of view (cf. Sitou and Spanfelner, 2007, Bauer and Spiekermann, 2011). We define context as the sum of "measurable and logically disjunctive information units, all of which must be combined to create an adaptive service" (Bauer and Spiekermann, 2011).

While a *context model* specifies relevant context for a particular context-adaptive service or system, a *context meta-model* structures context on a generic meta-level and is not bound to any specific system.

Already in the 1990's, some scholars recognized the need to define and structure context. Since then, a scale of context meta-models has been proposed. Common categories used to understand context include a user's location and environment, the identities of nearby people and objects (entities), and changes to those entities (Dey, 1998, Schilit et al., 1994).

Basically, we differentiate existing context meta-models by their *degree of abstraction* from the real world context. Context meta-models with a high level of abstraction depict the context world with a few generic categories. Context meta-models with a low level of abstraction typically depict the context world on two levels, with rather generic categories on the first level of abstraction and more specific categories on a deeper level. Frequently explicit examples enrich these models (on a third level of abstraction). Table 1 provides an overview of 13 context meta-models with their context categories, grouped by their level of abstraction.

publication	**level of abstraction**			**additional information**
	1st level	**2nd level**	**3rd level**	
high level of abstraction				
Chen and Kotz (2000)	physical environment			build on Schilit et al. (1994)
	user environment			
	computing environment			
	time			
Sitou and Spanfelner (2007)	operational environment			closely geared to Tarasewich (2003); considers change over time
	participants			
	activities			
Han et al. (2008)	user with his or her internal context			considers time by including past, present, and future on a time line
	social context			
	physical context			
Black et al. (2009)	task			
	location			
	objects			
Schilit and Theimer (1994)	user's location and environment			
	the identities of nearby people and objects (entities)			
	changes to entities			
Schilit et al. (1994)	physical environment	e.g., lighting, noise level		where you are, who you are with, and what resources are nearby
	user environment	location		
		collection of nearby people		
		social situation		
	computing environment	available processors		

		devices accessible for user input and display		
		network capacity		
		connectivity		
		costs of computing		
Bradley and Dunlop (2005)	user's world	incidental		combines and builds upon existing models from linguistics, psychology, and computer science
		meaningful		
	application's world	incidental		
		meaningful		
	contextual world	task		
		physical context		
		social context		
		temporal context		
		cognitive context		
		application's context		
low level of abstraction				
Rodden et al. (1998)	infrastructure context	people		categories are enumerated in an unstructured manner
	application context	devices		
	system context	objects		
	location context	presence		
	physical context	identity		
		space		
		time		
		position		
Schmidt et al. (1999a)	environment	human factors		
		physical space		
	self	user	physiological state	
			cognitive state	
		device	device state	
	activity	task		
		user behaviour		
Schmidt et al. (1999b)	human factors	information about users themselves		considers time aspect as context history over time
		users' social environment		
		users' tasks		
	physical environment	location		
		infrastructure		
		conditions	light	
			pressure	
			acceleration	
			audio	
			temperature	
Tarasewich (2003)	environment	location and orientation of objects		considers time with respect to present, past, and future
		physical properties		
		brightness and noise levels		
		availability		
		quality		
	participants	location and orientation		
		personal properties		
		mental state		
		physical health		
		expectations		
	activities	tasks and goals of participants		
		events in the environment	e.g., weather	
Zainol and Nakata (2010)	extrinsic context	physical environment		
		social environment		
		computing entity		
		location		
	intrinsic context (user)	user's personal profile		
		preferences		
		emotional state		
	interface context	activity		
		service		
Sigg et al. (2010)	location	geographical		
		relative		
	time	period		
		relative		
	activity	action		
		task		
	constitution	biological		
		mood		
	environment	physical		
		technological		
		equipment		
	identity	user		
		social		
		organizational		

Table 1. Overview of context meta-models with their levels of abstraction

3 Methods

In this work, we compare the 13 context meta-models as presented in Section 2.2 with respect to their scope (context meta-model comparison). In doing so, we investigate how well existing context meta-models cover the context variables used in this research area. Furthermore, we evaluate how well the context categories of these meta-models are reflected in research practice in the pervasive computing field (context meta-model validation).

The specific research questions are: How similar are the existing context meta-models? How comprehensive are these context meta-models? How well are the context meta-models reflected in pervasive computing research practice?

3.1 Model comparison approach

We iteratively reviewed the context meta-models as described in Section 2.2. Adopting an inductive approach, we first identified the context variables on the top level of abstraction that were named identically in several meta-models and grouped them accordingly. Other context variables had temporarily built separate groups. Reviewing these 'temporary' groups for semantic conformity led to a reduction of groups. The meta-models' context variables on the second level of abstraction were used to ensure that semantic conformity was interpreted as intended by the models' authors. Further brainstorming and group discussions led to a refinement of the grouping structure. In a final step, names were given to the resulting groupings, which we refer to as 'context dimensions'.

3.2 Validation approach

To develop an effective sampling strategy, we made a scoping review of the published literature. We decided to take the sample from IEEE Pervasive Computing Magazine, since this is the main outlet of the scientific and professional community in the field. We included all full-length articles of the IEEE Pervasive Computing Magazine, from 2005 through to the articles available in June 2011 (volume 4, issue 1 – volume 10, issue 2).

The following article categories of the 'IEEE Pervasive Computing Magazine' were included in the sample: Applications, News, Smart Phones, Spotlight, Standards & Emerging Technologies, Wearable Computing, and Works in Progress. Out of the 414 articles in the scope of the reviewed issues, a total of 297 met our inclusion criteria.

The coding procedure had three steps:

In a first step, we extracted basic information from each article: (1) author and year of publication, (2) title of the article, as well as (3) volume and issue. Additionally, two reviewers coded inductively from raw data (the articles) and obtained the following information: (4) explicitly stated context variables (i.e. the word or any deflection form of it is explicitly mentioned in the article) and (5) implicitly stated context variables (i.e. the context variable is circumscribed in the article; e.g., 'rate of the vehicle's speed change' is coded as 'acceleration and deceleration'). A total of 10,498 variables (9,867 explicit, 631 implicit) were coded (including duplicates among different articles, while duplicate occurrences within one article were filtered).

In a second step, we applied a 'word stemming' procedure for the explicitly and implicitly stated context variables. This procedure eliminates redundancy by uniting different terms that have the same base form. For example, 'locations' is coded as 'location'. Applying the word stemming procedure resulted in 3,742 distinct context variables (meta-codes).

In a third step, we took a deductive approach using the context dimensions as outlined in Section 4.1. Two reviewers allocated each coded variable (meta-codes) to a corresponding context dimension, if a corresponding one existed. All meta-codes that could not be allocated to one of the context dimensions were subsumed under the general term ‘others’.

Two reviewers coded each article and jointly built the classification scheme. In nearly every case, agreement on all coded dimensions was obtained. In the few instances, where some disagreement emerged, the reviewers discussed the variable in question until consensus could be established.

4 Results

4.1 A comparison of context meta-models

By iteratively reviewing the context meta-models as described in Section 2.2 we could identify six overarching context categories, which we refer to as context dimensions. Table 2 provides an overview of the six context dimensions and indicates which dimensions the various context-meta models cover.

authors	**context dimensions**					
	physical world	**individual**	**social groups**	**activity**	**technology**	**change over time**
Schilit et al. (1994)	physical environment	user environment			computing environment	
Schilit and Theimer (1994)	location, objects	identities of people				changes
Rodden et al. (1998)	location, physical				application, system, infrastructure	
Schmidt et al. (1999a)	environment	self		activity		
	physical	*physiological state, cognitive state*	*social*	*behaviour, task*	*device state*	
Schmidt et al. (1999b)	physical environment	human factors				change over time
Chen and Kotz (2000)	physical	user			computing	time
Tarasewich (2003)	environment	participants		activities		present, past, future
Bradley and Dunlop (2005)		user			application	
Sitou and Spanfelner (2007)	operational environment	participants, internal		activities		change over time
Han et al. (2008)	physical		social			past, present, future
Black et al. (2009)	location, objects			tasks		
Zainol and Nakata (2010)	extrinsic	intrinsic			interface	
Sigg et al. (2010)	location, environment	identity, constitution		activity		

Table 2. Overview of context meta-models with their context categories

The ‘physical world’ refers to everything concerned with the physical environment, the location (e.g., absolute location, relative orientation), and objects as part of the physical environment. While the dimension ‘individuals’ connotes context that concerns single persons and not groups (e.g., identity, eye colour, physiological states), the dimension ‘social groups’ refers to groups in their social environment (e.g., community, social pressure). Furthermore, the meta-models seem to use activity and task as closely related terms describing very similar variables. We therefore joined these two concepts as one dimension termed ‘activity’. In defining the infrastructure category, most authors actually refer to computing resources, networks or communication infrastructure. Accordingly, we subsumed this category under the dimension ‘technology’ (e.g., device, computing environment, application). Additionally, we believe that this term seems to better reflect this type of context. Most – but not all – context meta-models consider changes to context variables (over time) as separate context variable. We reflected this by keeping ‘change over time’ as a separate context dimension (e.g., changes, past-present-future).

Interestingly, although ‘identity’ is frequently mentioned in enumerative definitions and simple taxonomies of context (Dey and Abowd, 2000, Rodden et al., 1998), it is rarely used explicitly in the context meta-models (e.g., Sigg et al., 2010). Most models consider identity as a facet of the ‘individuals’ dimension.

4.2 Context-dimension validation: Context dimension richness

As reported in the methods section, data includes a total of 3,742 distinct meta-codes. Figure 1 illustrates the distribution of meta-codes among context dimensions. The more meta-codes a dimension refers to, the ‘richer’ it is. However, a high number of meta-codes also indicates that the respective dimension is rather complex and potentially too broad to support system designers.

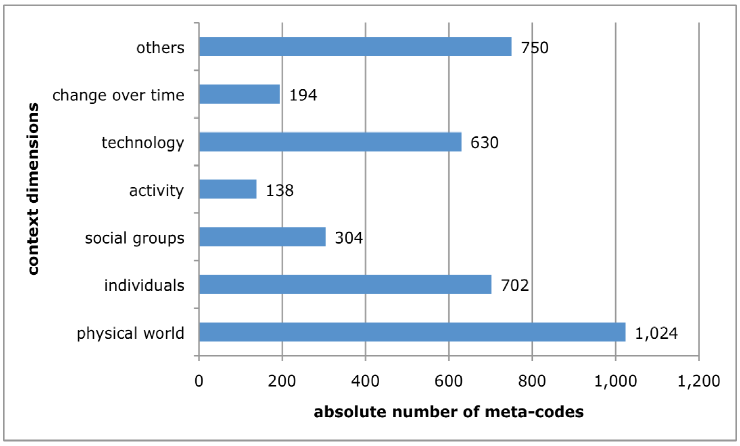

Figure 1. Number of meta-codes describing the context dimensions

The dimension ‘physical world’ is the richest context dimension. Here we identify that this dimension is rather broadly defined and accordingly subsumes a scale of meta-codes (1,024). Thereof, the variable ‘location’ alone accounts to 340 different meta-codes. The multi-facetted way of describing the subtleties of location is confirmed by Dobson (2005), who demonstrates a non-exhaustive taxonomy of eighteen distinct ways to locate a person.

The dimension ‘individuals’ is described by 702 different meta-codes. This strong representation may be due to a strong focus on human-computer interaction in the community. Furthermore, this high number reflects the complexity of human beings. For instance, the ‘individuals’ dimension includes personality traits, people’s behaviour, physiological aspects, and attitudes.

As soon as people interact with other people or organisations, we refer to it as the ‘social groups’ dimension. 304 meta-codes describe these phenomena, which ranges in the middle.

Similar to the ‘individuals’ dimension, also the ‘technology’ dimension is strongly represented (630 meta-codes). This is not surprising because the pervasive computing community is strongly represented by computer scientists who approach the field from a technical perspective and work towards technology advancement. Furthermore, similar to human beings, also the technology and computing field is very complex.

When analysing the dimension ‘activity’ (138 meta-codes), we identify that a large part of the meta-codes rather refer to some abstract concept of activity (e.g., action, activity type, task, work) rather than specific activities (e.g., food intake, gaming, smoking).

The ‘change over time’ dimension (184 meta-codes) covers some variables related to temporality (e.g., time of day, duration, period, time interval, time stamp). The remainder relates the time aspect with some other concept (e.g., asynchronicity, delay, lifetime, latency, time pressure) or a specific activity (e.g., shopping time, arrival time, production time); accordingly, the change over time of some variable is in the focus.

Remarkable is the fact that 750 meta-codes (20 percent) could not be allocated to any of the six context dimensions and had to be subsumed under ‘others’. This clearly indicates that the context meta-models are incomplete and do not cover the largest part of meta-codes.

When considering data from a context meta-model perspective (Figure 2), it becomes even clearer that the context meta-models cover only a fraction of potential context variables.

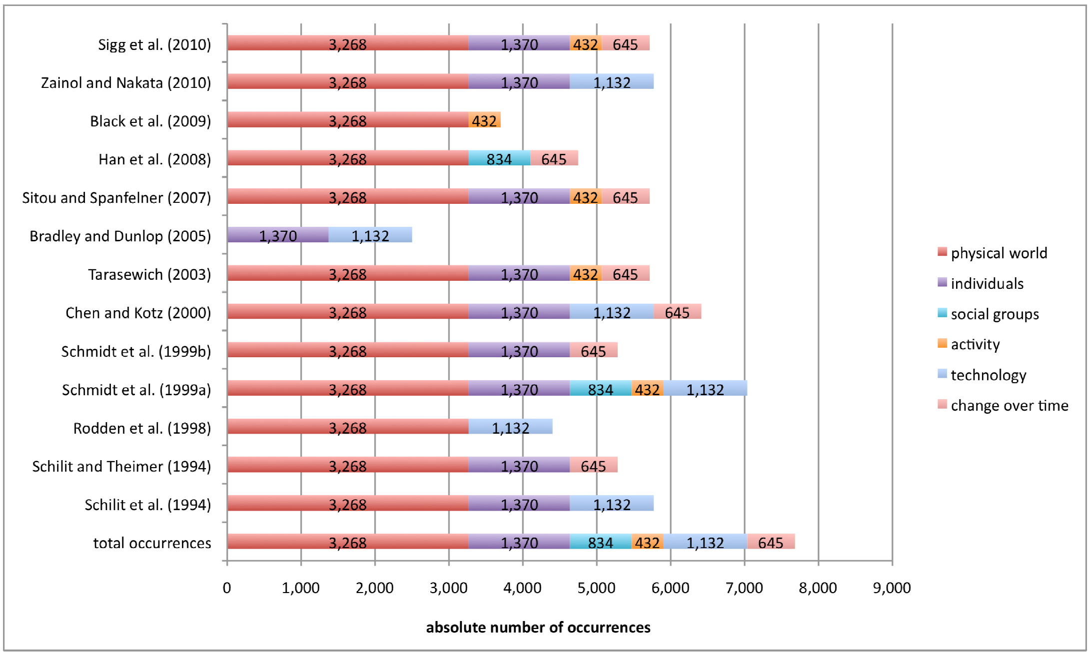

Figure 2. *Context dimension occurrences covered by context meta-models*

The context meta-model by Schmidt et al. (1999a) shows a relatively high coverage of context variables. Chen and Kotz (2000) are also doing well with their context meta-model. Although they consider only some context dimensions, their model integrates the ones that are well described with a scale of meta-codes.

Interesting items that are not covered by existing meta-models, for instance, refer to abstract, non-tangible concepts such as confidentiality, ownership, risk, threat, control, cost, easiness, simplicity, distraction, or usefulness. Other examples refer to characteristics and quality aspects such as feasibility, plausibility, efficiency, accuracy, precision, obtrusiveness, correctness, or constrainedness. Furthermore, items related to information and content (e.g., news, recommendations, content types,) are not part of existing context meta-models.

4.3 Meta-model validation: Reflection of context meta-models in pervasive computing research

While the previous section analysed the comprehensiveness of context meta-models, this section outlines how well these meta-models are reflected by research in the pervasive computing field.

For this purpose, we reviewed each of the 13 context meta-models for each context dimension. We analysed how many times (explicit and implicit occurrence frequencies) each context variable was mentioned in the article sample. In doing so, we have taken a context dimension perspective, indicating that we summed up frequencies of context variables for the respective context dimensions. The comparison matrix is provided in Table 3.

context dimensions	total occurrences	explicit occurrences	implicit occurrences	Schilit et al. (1994)	Schilit and Theimer (1994)	Rodden et al. (1998)	Schmidt et al. (1999a)	Schmidt et al. (1999b)	Chen and Kotz (2000)	Tarasewich (2003)	Bradley and Dunlop (2005)	Sitou and Spanfelner (2007)	Han et al. (2008)	Black et al. (2009)	Zainol and Nakata (2010)	Sigg et al. (2010)
physical world	3,268	3,042	226	x	x	x	x	x	x	x		x	x	x	x	x
individuals	1,370	1298	72	x	x		x	x	x	x	x	x			x	x
social groups	834	817	17				x						x			
activity	432	420	12				x			x		x		x		x
technology	1,132	1,080	52	x		x	x		x		x				x	
change over time	645	602	43		x			x	x	x		x	x			x
others	2,817	2,608	209													
covered occurrences in sample				4,370	4,283	4,287	5,636	3,883	5,015	4,315	2,502	4,315	3,447	1,832	4,370	5,542

Table 3. Context variable category occurrences matrix for context meta-models

Data reflects a wide range of context variable usage. As already mentioned in the methods section, we could identify 3,742 distinct context variables (meta-codes). These were represented by a total of 10,498 occurrences in the articles.

The most frequently considered context dimension in research practice is ‘physical world’ (3,268 occurrences), which is covered by almost all context meta-models. Widely discussed is also context related to ‘individuals’ (1,370 occurrences). Technology (1,132 occurrences) is fairly used in research practice on pervasive computing. Although ‘time’ and ‘change over time’ is included in a scale of meta-models, this category is hardly picked up in research practice (645 occurrences).

Interestingly, the ‘location’ – as a part of the dimension ‘physical world’ – has its particular significance on its own. As a separate context dimension, it would even rank three (1,287 occurrences). We may assume this high usage of location is due to its importance for mobile applications, in particular for location-based services.

Concerning the total sum of covered occurrences in the sample, the context meta-model by Schmidt et al. (1999a) is the most comprehensive one (Figure 3). Still, care has to be taken when interpreting the absolute figures per context meta-model because the number of occurrences of variables subsumed by ‘others’ could not be counted due to their vague definitions. Still, the model leaves out the important variable ‘location’, which would account for 1,287 occurrences of the calculated number of total occurrences for the model as given in Table 3.

The context meta-model by Sigg et al. (2010) also does well in covering the variables that are highly researched (5,542 occurrences). It, though, leaves out the category ‘technology’, which would account for additional 1,132 occurrences.

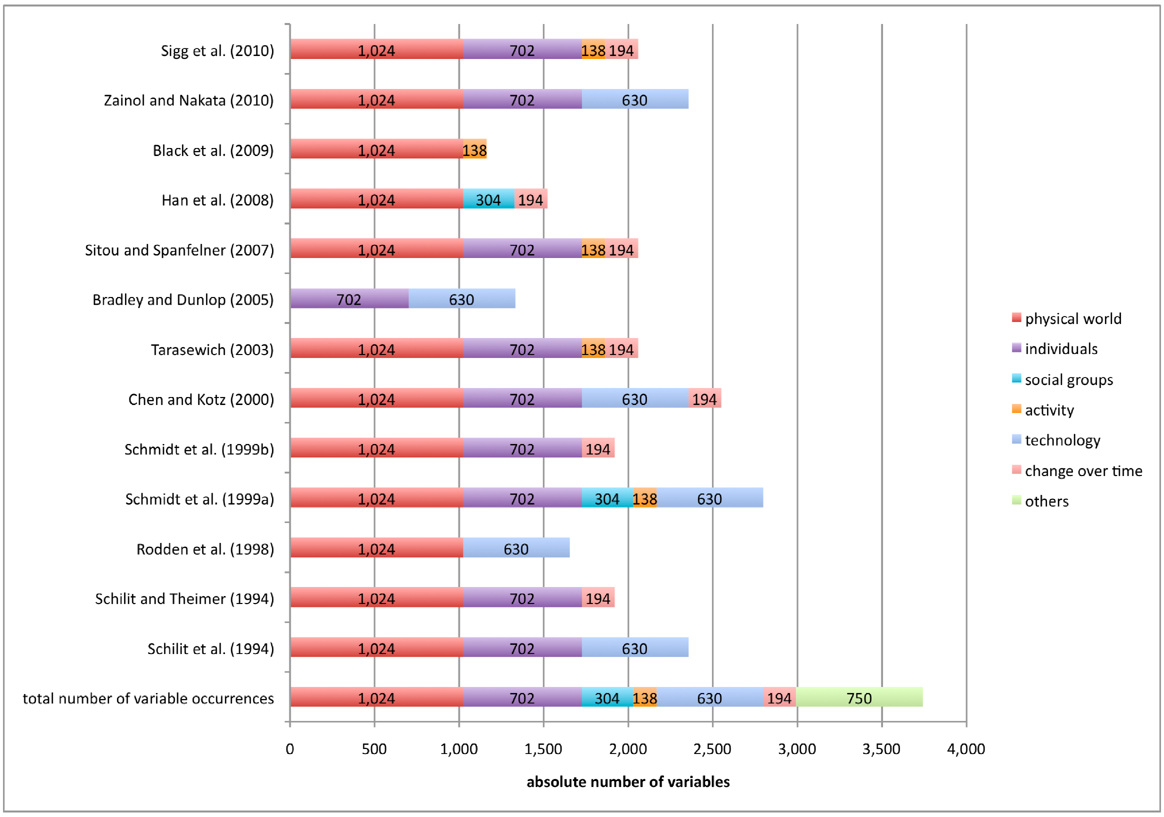

Figure 3. Number of variables per context dimension covered by context meta-models

5 Discussion

The results indicate that the scale of context meta-models with their various context categories can be narrowed down to six context dimensions. This lets conjecture that the context meta-models are quite similar. However, many of the presented context meta-models integrate only three context dimensions. For instance, the context meta-models by Han et al. (2008) (physical environment, social environment, past, present, future, and internal environment) and by Black et al. (2009) (location, objects, tasks) do not have any overlaps. Consequently, we suggest that the various context meta-models are different.

Moreover, data reveals that existing context meta-models are not comprehensive because each covers only a fraction of meta-codes while the rest of the identified meta-codes is out of scope. Although we can see that broadly defined concepts (e.g., the context dimension ‘physical world’) cover a wide scale of meta-codes, we would miss our target by integrating generic and broad dimensions only. While generic concepts may give a clue about what context is generally and theoretically, from a requirements engineering view, very generic concepts are insufficient. System designers find it difficult to come up with some specific idea of a concrete context variable for a specific system or application, when research provides only generic concepts on a high level of abstraction. In addition, the vast number of meta-codes found in the data demonstrates that context is a very complex construct. Accordingly, it appears almost impossible to establish a simple model that includes all thinkable variants of context variables. And be it that some researcher succeeds in doing so, it is very likely that the model’s components would be so generic or abstract that they are useless to system designers.

Overall, the context meta-models are well reflected in the sample, as all the models' dimensions could be met with a scale of context meta-codes. Thereby, some context dimensions are far more frequently discussed than others. For instance, the dimensions 'physical world' and 'individuals' are widely discussed, while the dimensions 'activity' and 'change over time' receive only very little mentioning. However, 27 percent of total occurrences of context variables (2,817 occurrences) could not be clearly attributed to any context meta-model. This finding reveals that research practice in pervasive computing (system development and technology advancements) is far ahead of research dedicated to model development. Moreover, this is a clear indicator that the research community does not 'stick' to existing meta-models of context when elaborating their research. Yet, in this context, it appears to be advantageous because it seems that reality has much more to offer than current meta-models express.

6 Conclusions

The context-aware and pervasive computing community has grown rapidly since the 1990's. And still it lives without a clear-cut definition of what builds the core: context. Several meta-models of context exist that postulate to frame the basis of what is understood as context.

This work compared 13 context meta-models with respect to their similarities and differences. While it could be shown that the models' categories could be narrowed down to six context dimensions, analysis also revealed strong differences because many of the context meta-models integrate only three dimensions.

Additionally, we empirically validated the context meta-models against all context variables mentioned in the Pervasive Computing Magazine in the last six and a half years. Data revealed that 20 percent of variables were not covered by any of the analyzed context meta-models.

Accordingly, there is a clear appeal to the community to dedicate efforts to basic research because the research field needs theories that reflect reality. With this paper we could demonstrate that there is much more that is context than what current context meta-models define. Furthermore, data demonstrate that pervasive computing researchers do not act upon their field's theories (context meta-models) but rather go their own way. However, the research community needs to elaborate and advance its basic theories continuously such that research practice reflects theories and theories also reflect current research endeavours. In other words, research needs to undergo a continuous process of conceptualizing context.

Against this background, future work will suggest a context meta-model that reflects research practices and integrates recent findings. The key appears to be a thorough conceptualization of context, which considers the various aspects of context information. Thereby we emphasize that the conceptualization of context is a dynamic process.

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