Using Building Data Models to Represent Workflows and a Contextual Dimension

by

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I hereby declare that I am the sole author of this thesis.This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

The context-workflow relationship is often poorly defined or forgotten entirely. In workflow systems and applications context is either omitted, defined by the workflow or defined based on a single aspect of a contextual dimension. In complex environments this can be problematic as the definition of context is useful in determining the set of possible workflows. Context provides the envelope that surrounds the workflow and determines what is or is not possible.

The relationship between workflow and context is also poorly defined. That context can exist independently of workflow is often ignored, and workflow does not exist independently of context. Workflow representations void of context violate this stipulation. In order for a workflow representation to exist in a contextual dimension it must possess the same dimensions as the context.

In this thesis we selected one contextual dimension to study, in this case the spatial dimension, and developed a comprehensive definition using building data models. Building data models are an advanced form of representation that build geometric data models into an object-oriented representation consisting of common building elements. The building data model used was the Industry Foundation Classes (IFC) as it is the leading standard in this emerging field.

IFC was created for the construction of facilities and not the use of facilities at a later time. In order to incorporate workflows into IFC models, a zoning technique was developed in order to represent the workflow in IFC. The zoning concept was derived from multi-criteria layout for facilities layout and was adapted for IFC and workflow.

Based on the above work a zoning extension was created to explore the combination of IFC, workflow and simulation. The extension is a proof of concept and is not intended to represent a robust formalized system. The results indicate that the use of a comprehensive definition of a contextual dimension may prove valuable to future expert systems.

Acknowledgements

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Chapter 1

Introduction

1.1 Background Information

1.1.1 Workflow

The word workflow has been used to describe many types of objects. Workflows describe the allocation and use of resources as repeatable processes. The basic building blocks of a workflow are resources, processes and routes. Resources such as actors, activities and entities, are objects related to a workflow that interact with the processes in a workflow as it advances along specified routes.

As objects, workflows are commonly represented using flowcharts, process maps, graphs and other 2-dimensional figures. These examples are static representations of activity, commonly referred to as classic workflow representation techniques. Classic workflow representation techniques are able to represent resources and activities but do not adequately capture other elements associated with the workflow (Covvey et al., 2007) such as the relationship between the workflow and organizational context.

1.1.2 Defining Context

Context is the environment in which workflows exist and can be both tangible and intangible. Figure 1.1 visualizes this interpretation of context as a multi-dimensional entity.

Context is not one element, but a collection of any number of elements that combine together to form a description of the environment that workflows exist in.

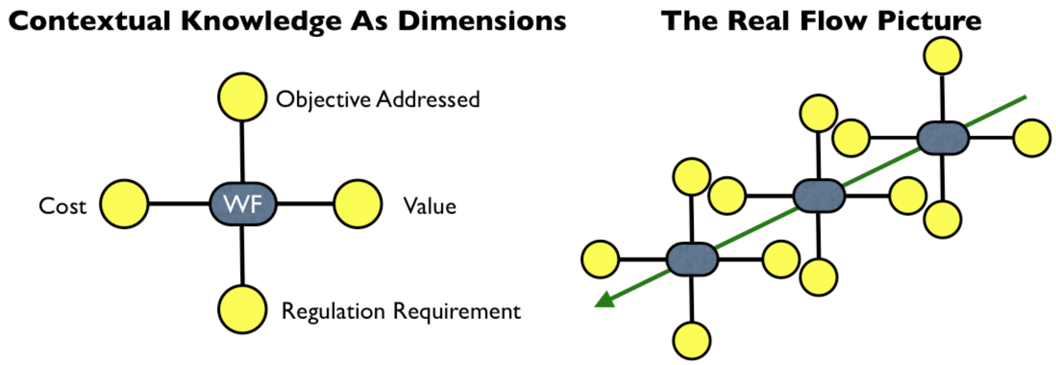

Figure 1.1: Visualization of Workflow Context

The contextual dimensions of a workflow can include the physical limits imposed by a facility, government regulations, financial limitations and organizational goals. This is not an exhaustive list but represents the common dimensions (Covvey et al., 2007).

The dimensions can be broken down into sub-contexts (or sub-dimensions) to provide the required amount of granularity in the description of the environment. We will be retaining a macro definition of contextual dimensions to avoid confusion with respect to the enumeration of sub-contexts.

The nature of the relationship between context and workflow is not fully understood. We know that workflows exist in a context and inherit its dimensional characteristics, but the details of how the two interact are unclear. Examining this relationship from the perspective of all the contextual dimensions related to workflow is a challenging problem. At this stage we will select one contextual dimension and its interaction with workflow to study in detail.

1.1.3 The Selection of a Contextual Dimension

Some dimensions vary over time, while others remain largely static. This distinction between the two is referred to as the “consumability” of a dimension. With consumable dimensions such as money, the workflow requires the availability of the portion of a resource, and on completion of a process, will remove it from the available pool permanently. A non-consumable dimension such as a hallway for transportation purposes may require the availability of the resource but does not remove it permanently from the available pool on completion.

In a study of the relationship between workflow and context, a tangible non-consumable dimension is a desired starting point. The spatial dimension meets these criteria as it is the 3-space geometric representation of a workflow. It will also facilitate visualizations of the workflow and the environment.

1.2 Problem Statement and Objectives

The nature of the relationship between context and workflow is not explicitly defined. By performing an in depth examination of one contextual dimension as it relates to workflow, we arrived at a better understanding of the relationship between the two. The first step in this process was to analyze existing workflow systems and their definitions of context. The information from this study was used to determine if systems exist to provide a contextual representation of workflow. None were found, so we used the results to create an outline for the construction of a system that provided the framework to study the interaction between workflow and context.

The ability to study this interaction is defined by the system's ability to visualize workflows, the contextual dimension under study and their relationship to one another. The key measure of such a system is the level of detail and flexibility it provides in their representations as workflows and contextual dimensions can be complex and require significant amount of information to describe them properly. Given the lack of precedent in this research, the creation or modification of an existing spatial model was required. With this in place we determined what information is available on the interaction between workflow and context and if it can be applied for future research. If successful this research is intended to be used as a template for future study of other dimensions in the workflow-context relationship.

The primary focus of this work is in the representation and visualization of the workflow and determining if a suitable system can be created to study this relationship. Once this was established we moved on to address some of the major concerns in previous workflow representations. One concern that exists with the use of classic workflow representation techniques is the difficulty in analyzing their effectiveness; otherwise known as the process of workflow evaluation. Through the creation of a new method of representation for workflows, we began the discussion on whether or not the inclusion of contextual information can lead to improvements in workflow evaluation. The discovery of links between the environment and workflow evaluation software provide evidence that performance improvements are possible, but the limits of this improvement are unknown.

1.2.1 Contributions

The primary contributions of this thesis are outlined in this section to provide an overview of the new material covered.

1. An analysis of the existing workflow representations with respect to at least one contextual dimension (Chapter 2).

2. Discovery of a means to visualize a workflow within a contextual environment using building data models (Chapter 3).

3. Created the concept of de-coupled workflow descriptions to describe the barriers in creating systems to relate workflow to the contextual environment (Chapter 4).

4. Development of a zoning technique to describe/visualize workflow in a contextual environment (Chapter 4).

5. Developed a prototype system to combine description of contextual environment with a workflow simulation application (Chapter 5).

6. Found that this single application combination provided some exciting avenues for future research, but was inconclusive in its current format (Chapter 5).

1.3 Thesis Organization

This thesis consists of 6 chapters and 5 appendices. Chapter 2 examines the literature related to this study including current techniques for representing and visualizing workflows. It then analyzes these techniques as they relate to their expressiveness of workflow contextual elements. Chapter 3 will detail the model development and the adoption/implementation of the Industry Foundation Classes (IFC) for representing the contextual environment. It will also analyze its pros and cons of its adoption for workflow. The chapter will conclude with an initial solution and an analysis of its limitations with respect to the representation of workflow and context.

Chapters 4 and 5 are the focal points of this project as they discuss the combination of workflow and IFC. Chapter 4 consists a discussion on the visualization of workflow with IFC models based on the results of chapter 3. Chapter 4 concludes with a zoning technique to create a coupled workflow system. A prototype design for combining the contextual information derived from an IFC representation with workflow and simulation is discussed in chapter 5 to build on the work from chapter 3.

This prototype was found to be limited and required additional research to create a more robust solution. This paper concludes with conclusions and directions for future research in chapter 6. Appendices A-E appear after chapter 6 and include a discussion on the structure of a sample IFC facility, a reference of workflows used in prototype implementations, an explanation of the zoning concept, a glossary of terms and a complete list of references.

Chapter 2

Representations of Workflows and Context

The literature reviewed included studies of workflow, workflow management systems as well as other systems that utilize workflow in their implementations. The goal was to understand the philosophical motivations of each and to develop an understanding of the relationship between context and workflow. This placed the emphasis on the structure of the various implementations and not on measuring their end performance or technical specifications.

2.1 Workflow and Context

Classic workflow representations typically do not include contextual information. One theory as to why this occurs is that workflows have evolved from a description of the flow of paper and have since been abstracted for use in multiple domains (Sauer and Maximini, 2006). As activity-centric descriptions of work, workflows were created independently of context.

There are several types of systems that have been developed that extend the workflow concept beyond classic representations. Workflow management systems (WfMS) are systems used to automate processes by coordinating and controlling the flow of information and work among participants (Stohr and Zhao, 2001).

Maus identifies the need for context in order to automate processes but asserts that modern WfMS do not contain a comprehensive representation for workflow context (Maus, 2001). In his work he includes a definition of context and a break down of the contextual information required into three sources; workflows, organizational memory and contextual knowledge (Fig. 2.1).

Figure 2.1: The Dimensions of the Workflow Context Space (Maus, 2001)

The context is defined by the workflow or expert knowledge and is utilized in further iterations but is not explicitly defined; in this system the workflow defines the context. Maus discusses possible classifications of context with respect to workflow but does not provide information on usable ontologies.

2.2 Simulation Studies

Simulation studies are concerned with the process of workflow evaluation. They examine a set of processes, or a workflow, typically represented using classical techniques and provide output data based on the model created by the designer.

In some applications, simulations may include contextual information. Examples include adding object travel time between process elements or relating the process map to a diagram of the layout of the facility.

With respect to the spatial dimension, overlaying the process map onto the facility floor plan creates a relationship between the workflow and the context. In simulation programs with visualization engines this allows stake-holders to view the simulation in progress in a visual setting, creating an implied relationship between the two. Figure 2.2 includes an example of a 2-D simulation study that utilizes a layout of the facility.

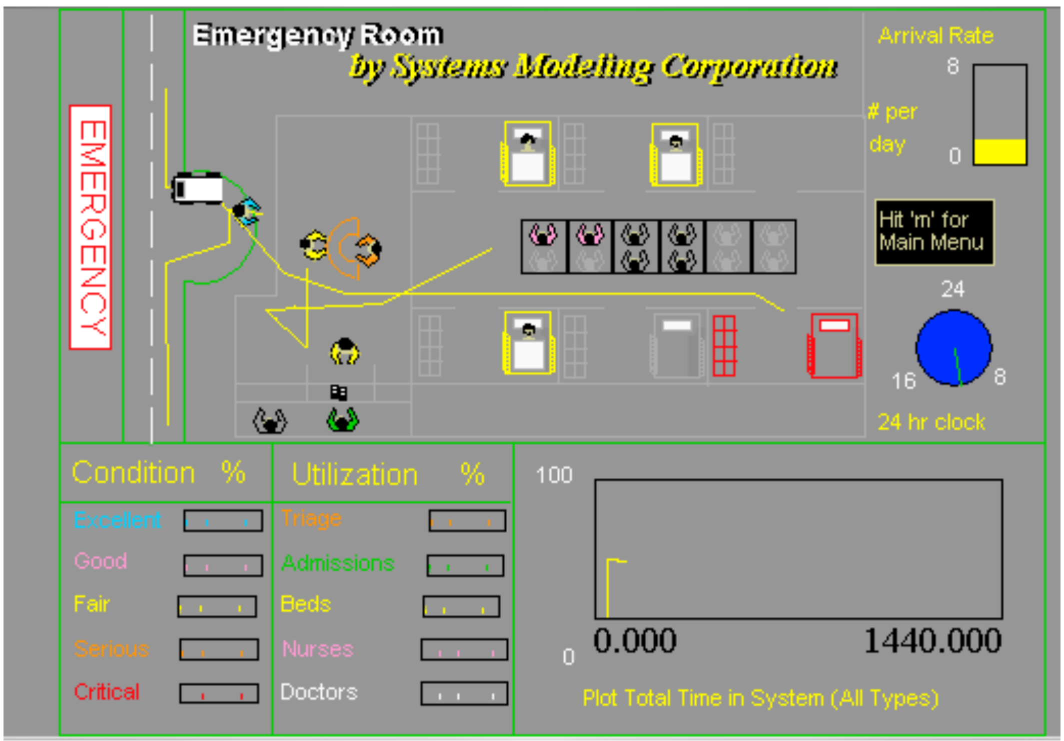

Figure 2.2: A Healthcare Simulation Using a Facility Layout (Systems Modeling Corp., 2002)

This method of representation uses a simple method to relate workflow to context. The projection of the workflow onto the layout creates a visual correlation that allows us to create connections between the two, but the relationship between the two is not formalized.

The contextual dimension, in this case the facility, is an image of the facility and possesses no properties aside from geometric relations. The act of placement of workflow elements on the image does not allow the workflow to inherit the dimensional properties of the contextual environment.

This visually superimposed layout is a de-coupled system between workflow and context. Altering the floor plan would not affect the simulation of the workflow since the floor plan is just an image of the facility. In this type of system the context and the workflow are only superficially related to one another. De-coupled representations are not suitable for our investigation given that we are attempting to develop a comprehensive understanding of the relationship between context and workflow.

Within a de-coupled system, interpretation of simulation output data can be subjective. The expected length of a queue may be meaningless without knowledge of what impact it has on the operation of other processes in the facility. This type of analytical operation may be performed by humans, but requires detailed knowledge of the context of the workflow in order to interpret it. Without the prior definition of this contextual information, evaluation of workflows is challenging.

In a coupled system, context and workflow would begin as separate definitions. It would also represent the contextual properties of the environment in order to link them to workflow. The simulation studies uncovered have no capacity for this due to a lack of complexity in the representation of the facility/context.

2.3 Facilities/Architectural Layout

Automated Facilities Layout (AFL) originated in the 1960's as a means to apply operations research techniques to improve facility design efficiency as the demand for computerized planning and management increased (Liggett, 2000). It has been used in multiple domains including VLSI design, hospital layout and service center layout (Yeh, 2006). AFL uses throughput to create a relationship between the workflow and the facility as the relative location of departments is critical to reducing bottlenecks and minimizing total travel time for processes in a facility (Elshafei, 1977).

Discovery of an optimal layout is accomplished by assigning the departments to an orientation within the facility based on an algorithm and input parameters. The assignment can be done in terms of 1-1 assignment, space as an area (many-1) or space as an area and a varying shape (Fig. 2.3).

AFL problems are typically formulated as a quadratic assignment problem which is an np-hard problem. The complexity of the problem has led to the use of heuristic techniques such as simulated annealing in order to generate solutions for large-scale problems (Yeh, 2006).

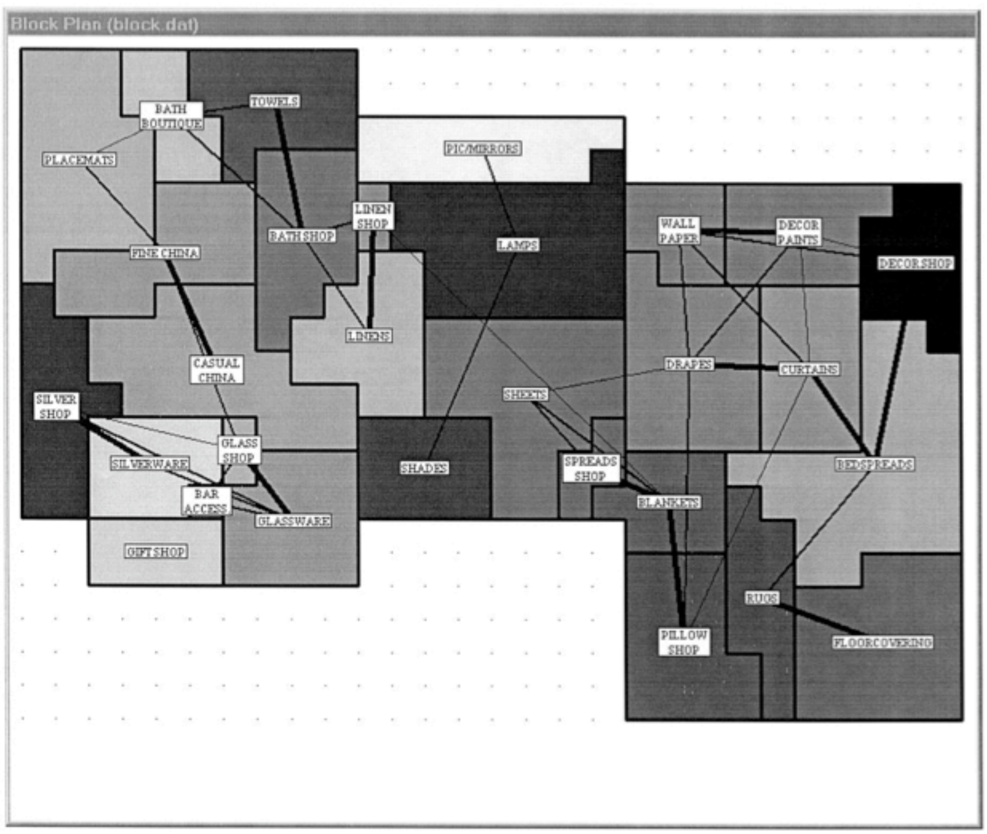

Figure 2.3: Example of AFL (Liggett, 2000)

The most recent example uncovered was from 2006 (Yeh, 2006). This paper stated that a more powerful solution technique using genetic algorithms had been applied to successfully solve larger scale problems. In the problem formulation, penalty factors are adjusted for departments on separate floors. No evidence is provided to describe how these penalty coefficients were established. In the conclusions, they point out that the choice of penalty coefficients has a significant impact on the optimal layout of a facility but that further research is required in order to understand what this choice of penalty factors should be.

Failings similar to these are discussed in Liggett's review of AFL. It reviews the solution techniques available at the time of publication and develops a road map for future research in the field. Liggett states that the future of AFL is in advanced systems that will feature the following 4 design characteristics:

- The ability to handle large scale problems
- A modern interactive interface
- Support for an iterative design process
- Links to CAD and FM databases

Further research was unable to uncover systems or applications built on these principles. It was able to discover systems that utilized some of the elements of Liggett's proposal.

2.4 Joint Systems

Joint systems fall into two general categories: comprehensive and expert systems. Comprehensive systems combine multiple OR solution techniques together to form iterative applications. Expert systems are defined as systems that incorporate models of contextual information in an attempt to account for all influences in the process of layout design (Azadivar & Wang, 2000).

2.4.1 Comprehensive Systems

An example of a comprehensive system is the SimStock application (Dawood & Marasini, 2002). This application was developed in order to generate the optimal layout of a stockyard using CAD models, workflow simulation and a knowledge database. The structure of the application can be found in figure 2.4.

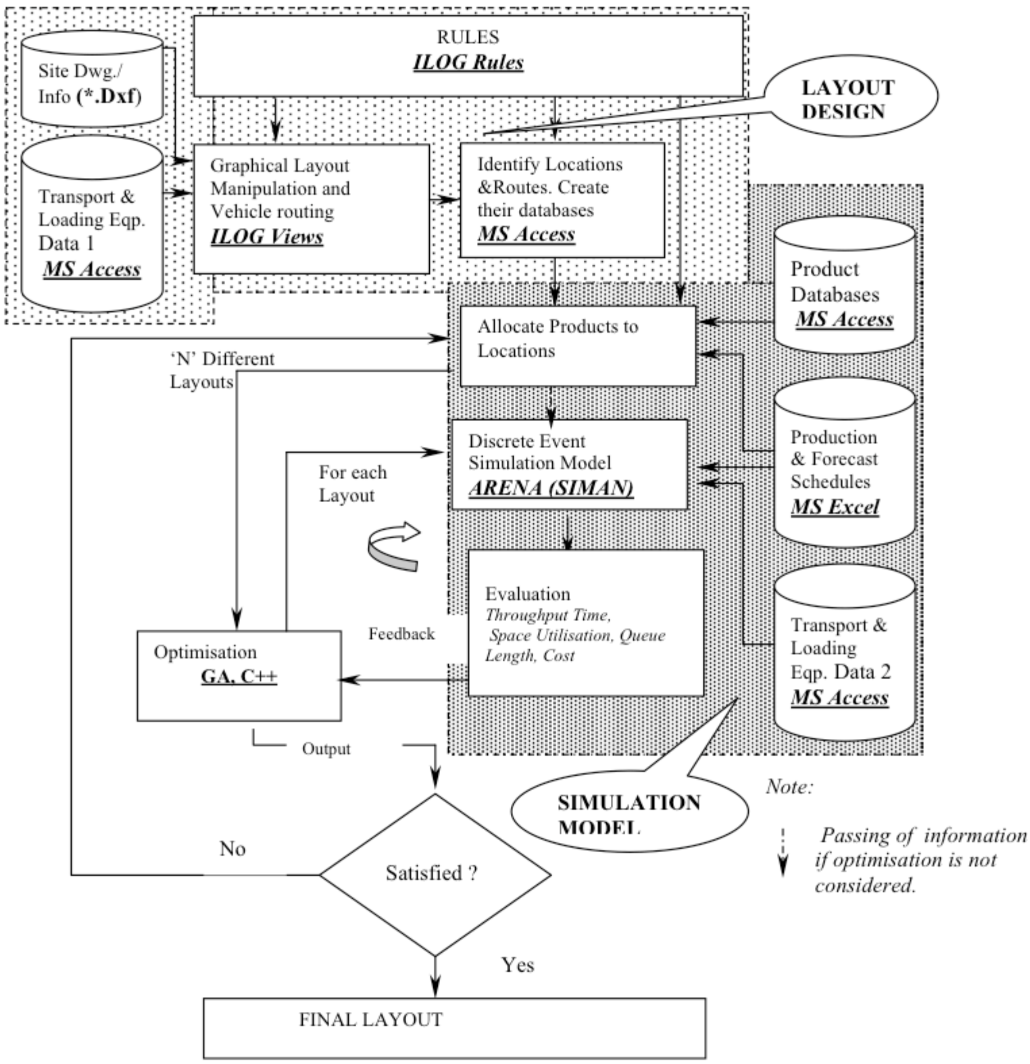

Figure 2.4: Simstock Data Model (Dawood & Marasini, 2002)

An iterative design process is used to determine the optimal assignment for product storage in the stockyard and the delivery routes utilized. Improved designs are generated by taking the simulation output data and using it to re-solve the problem using genetic algorithms. The system uses the integration of production and dispatch schedules as its knowledge base to provide additional information for iterative solutions.

A CAD model of the facility is used to define the geometric layout of a stockyard and the transportation pathways. During the solution process the orientation of the layout remains unchanged; it is the assignment of product to available lots that varies. This comprehensive system is de-coupled as the representation of the facility provides no additional contextual information aside from the geometric orientation of the lots.

2.4.2 Expert Systems

Early expert systems were conceived in the late 80's as a combination of a database, a knowledge base, an inference engine and a priority base used in the layout process to improve solutions (Malakooti & Tsurushima, 1989). Together they presented a combination of contextual information and rule systems to assist in the design process.

A more recent example of an expert system (Azadivar & Wang, 2000) developed an implementation that involved the combination of simulation and facilities layout techniques to improve solutions and solution times. While the paper demonstrated that this technique improved the time required to solve problems, it did not identify the definition of context utilized.

2.4.3 Joint Systems Summary

Joint systems are a step towards the coupled systems that we seek as they take elements of the contextual environment into account. They typically include advanced user interfaces, improved solution techniques to handle larger scale problems, an iterative design process and links to external information sources. This is a positive step towards addressing the criticisms outlined in Liggett's AFL review.

Among the joint systems studied, none were found that embodied the characteristics of a coupled system. Specifically they lacked a comprehensive representation of spatial contextual information aside from geometric properties available in a CAD model. All these representations have described facilities as a collection of geometric objects with no associated contextual information. In order to find a highly detailed representation that would focus on the properties and definition of the space, we turned to civil engineering and architecture literature.

2.5 Architecture, Engineering, Construction (AEC) Domain

Data models, in any domain, describe the attributes and entities of the domain as well as the relationships that exist between the entities in that domain (Khemlani, 2004). Within the AEC literature there are two data models used for the representation of space; *geometric data models* and *building data models* . *Geometric data models* define space in terms of geometric entities such as lines, points and polygons. Spatial representations that use CAD layouts are examples of *Geometric data models*. *Geometric data models* are problematic as contextual information contained within a facility extends beyond its geometric attributes; the size and shape of a wall does not indicate if it is load bearing and what impact its removal would have on the facility.

In response to this criticism, the AEC community has begun to develop object-oriented *building data models*. *Building data models* describe a space as a collection of common building objects with multiple properties. Figure 2.5 displays the difference between the geometric and building data models using an example of a room consisting of 4 walls and a space.

As demonstrated in Figure 2.5, a room is more than two rectangles when *building data models* are used; it is a collection of objects with pre-existing properties including a definition of the unused space in the room. The common building objects create a source of contextual information that defines the relationships between the entities.

2.6 Chapter Summary

The first stage of our study is complete. We have reviewed the pertinent literature in order to outline a path for future work. We revealed that there should be a definition of context with respect to workflow and that this definition should be independent of workflow. An examination of existing workflow applications revealed that they typically use a de-coupled representation in which the relationship between context and workflow is not formalized and contextual information was created on an as needed basis. Recent literature revealed a move towards joint systems that incorporate contextual information and attempt to

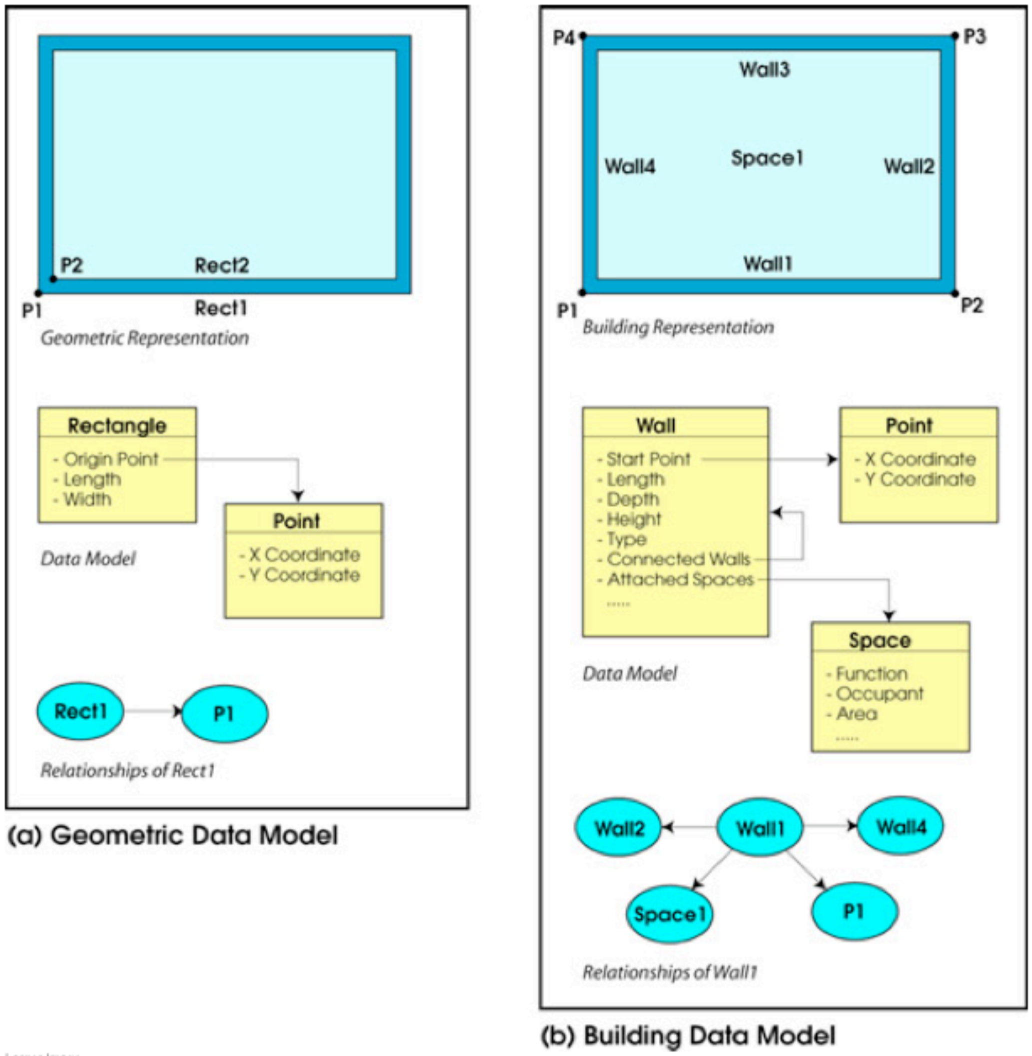

Figure 2.5: Data Model Comparison (Khemlani, 2004)

develop a coupled system. None of the joint systems studied were found to include an explicit definition of context aside from a geometric facility representation.

The detailed representations available in architecture/civil engineering provided the most appropriate representations for contextual information found in a facility. *Geometric data models* were presented as the typical models used in de-coupled systems. The alternative to geometric models is *building data models* which use an object oriented approach to define a facility in terms of common building objects.

Building data models offer the possibility of rich models of the environment unavailable in previous applications. The compatibility between them and workflow analysis applications remains unclear. *Building data models* were developed for the design of facilities, not necessarily for their future use by its occupants.

Chapter 3

IFC and Model Development

Building data models will be discussed at length in this chapter with respect to their applicability to our study of workflow representation and evaluation. Of the existing *building data models*, the Industry Foundation Classes (IFC) model was found to be a leading candidate for our use. We will conduct a detailed study of IFC in relation to workflow to determine if it is a suitable means of representation. The chapter will conclude with a discussion on a prototype for combining a *building data model* with a workflow and comparing it to our original research objectives.

3.1 Introduction to IFC

3.1.1 History of IFC

Software applications have been making use of *building data models* for over 20 years. Examples of architectural design applications that use *building data models* include ArchiCAD, Bentley Architecture and Autodesk Architectural Desktop. Widespread adoption of each has not been gained as each vendor used proprietary implementations. The lack of a common standard hampered interoperability between these applications and the others used in the design process.

Increased interoperability could lead to significant economic gains for AEC firms: it has been estimated that building owners could save $15.8 billion a year through the better coordination of electronic data (Phair, 2006). This is not to suggest that the adoption of a standard would necessarily lead to savings of this magnitude, but that interoperability has some economic backing.

The International Alliance for Interoperability (IAI) was formed in 1994 as a coalition of various members of the AEC community to seek means to extract economic value from the interoperability of AEC software. In 1997, IAI released IFC 1.0 as the first iteration of their *building data model*. During the development of IFC, the IAI expanded from a consortium of 12 US companies to a global partnership.

In order to achieve interoperability, IFC outlined a strategy to create a *building data model* that would include all objects and entities associated with the process of constructing a facility. This would include all the physical and abstract entities. To date, IFC does not include a definition of all these entities, though it does intend on including the remainder in future revisions.

3.1.2 Criticisms of IFC

IFC has been criticized in academic and commercial forums. Chief among the criticisms is that it is too complex and too detailed for most applications (Ozel et al., 2003). Another concern is that it possesses a significant learning curve and many of the applications based on the standard are still in the early stages of their development and are not suitable for large-scale projects.

One response to this line of criticism has been the creation of several competing standards such as AECxml and BMxml. These competing standards are simplified versions of IFC that are less cumbersome for designers. This is accomplished by containing fewer elements in the definition or using abstract definitions that are instantiated as required. The second option is analogous to our research in expert systems: the knowledge base is not defined explicitly and is defined on an as required basis.

Another source of criticism is that IFC does not include all building objects in its latest definition, thereby reducing its functionality (Ma et al., 2005). Without completeness in the definition, it may not be fully interoperable with all design applications.

We are looking for a representation that is highly detailed in order to provide a separate description of the contextual environment. We have not established which elements of the context are relevant to workflows, and as such will not limit ourselves at this stage with a simplified representation. The presence of criticisms suggest that IFC is being used and reviewed.

3.1.3 Applications of IFC

IFC is not an application but a data model that applications may be built on. In order to provide context on the use and relevance of IFC we will discuss current applications that utilize IFC.

Academic Applications

One example of IFC being used in academic research is in the domain of facility and architectural simulation. These include spatial, lighting, airflow and energy use simulations, but not workflow related simulations (Bazjanac and Crawley, 1997). The detailed model of the environment provides enough data to allow for vizualizations and calculations of the planned facility. An example of a stress test simulation can be found in figure 3.1.

Another example of IFC related research is a paper from the First International Conference on Semantics, Knowledge and Grid describing the process of converting IFC to OWL (Schevers and Drogemuller, 2005). The purpose of which is to create meaning in the underlying expert knowledge in IFC to improve with computer-assisted decision-making and design. The paper mentions that the conversion is possible but would require a modified definition of IFC in order to take advantage of the full feature set of OWL.

Commercial Applications

Since the launch of IFC, several of the applications, that used proprietary *building data models*, have become compatible with IFC. Applications that are now IFC compliant include Nemetschek's Allplan, Graphisoft's ArchiCAD, Bentley's Architecture, Autodesk's Revit, Tekla's Structures, Archimen's Active3D, and Solibri's Model Checker Architectural Desktop.

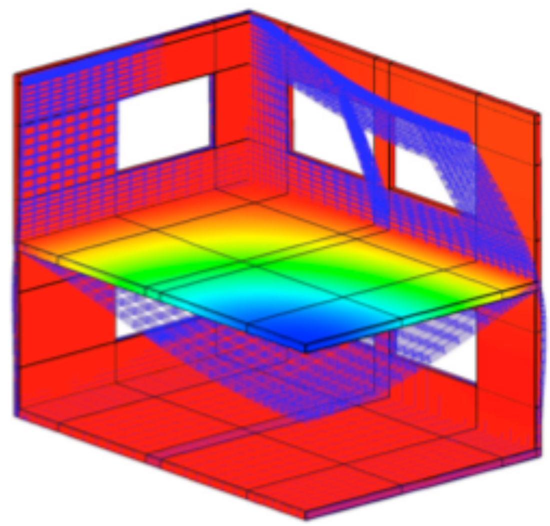

Figure 3.1: Stress and Displacement Simulation Caused by Vertical Loads (van Treeck et al., 2003)

Government Applications

There is some evidence to suggest IFC is being adopted by government agencies in smaller projects (PM4D, 2002) but none that any nation is adopting it as a regulated standard. One example of its use by a government agency is the US military's Fort Future program (Fort Future, 2003). The mission of this program to provide a group of tools to support sustainable planning using simulation at a national, regional and installation level. Several applications are used to achieve this goal, one of which is an IFC based facility composer application. The facility composer provides tools to allow designers to quickly and efficiently design a facility based on army requirements, and to compute its estimated cost. Version 1.0 of this toolset was released in October 2004, and version 2.0 was slated for release in October of 2007 but has been delayed. The existence of a second release suggests it has been found to be beneficial, but evidence to quantify this benefit could not be found.

3.1.4 Section Summary

Based on IFC's continual revisions, presence in the literature and use in applications we have found it to be a widely adopted standard for *building data models*. With this evidence in hand we will proceed in examining the structure of IFC.

3.2 IFC Architecture

The structure of IFC is closely related to STEP (ISO 10303). STEP is a standardization initiative started in order to provide an independent means of describing product data throughout its life cycle. In recent revisions of IFC, the specification has included an xml format for applications instead of the EXPRESS modeling language in order to make it interoperable with additional applications.

In IFC all facility components are referred to as entities. The latest specification contains 623 entity definitions, categorized into classes based on their shared characteristics. The entities are not all equal and are divided into 4 layers to provide a hierarchical meaning: entities of a given level may only reference entities on the same level or a lower level but not higher level entities. The 4 layers of the specification are the domain layer, the interoperability layer, the core layer and the resource layer. Classes and entities from the IFC architecture will be italicized for the duration of the thesis. An architecture diagram listing the major classes of IFC can be found in figure 3.2.

Domain Layer: The domain layer is the most specific layer in the IFC specification. The schemas of the domain layer are tailored to individual industries/domains. To date, none of these specifications have been approved as part of the IFC platform.

Interoperability Layer: This layer contains building elements which are common to multiple domains. These include beams, doors, walls, roofs and windows and their associated properties and enumerations. Of the five classes in the interoperability layer it is the *Shared Building Elements* which contain the physical objects of a facility; the other four contain abstract objects. *Shared Facilities* contains entities for asset listing and service scheduling, *Shared Management* is concerned with cost elements, *Shared Components* provides the ability to represent various accessories and fasteners and *Shared Building Service* contains entities for fluid flow, energy and sound properties of the facility.

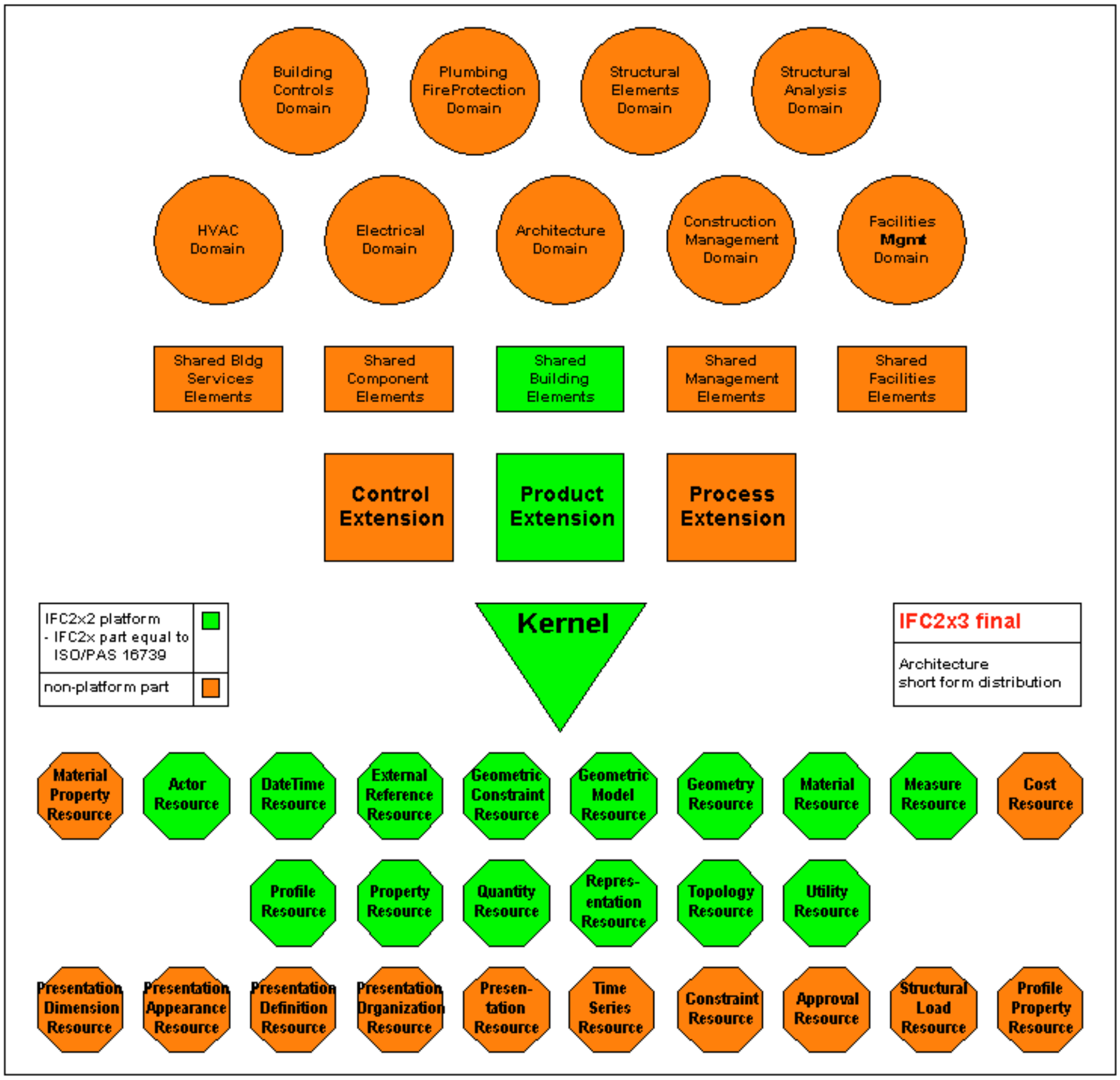

Figure 3.2: IFC Architecture Diagram (IFC Model Guide, 2004)

Core Layer: The core layer consists of definitions of the abstract concepts that are required to define the higher level entities. These abstractions are not industry specific and represent concepts such as actor, process, task and relationship. This layer consists of 3 extensions and a kernel which represents the most general constructs available in IFC.

Technically the core layer is separate from the *kernel*, but this is a distinction that is rarely made. The *kernel* was created to provide a bridge between the resource layer and AEC/FM specific constructs which exist on a different hierarchical layer. Of the 3 extensions, the product extension (50 entities) contains the facility abstractions *IfcBuilding*, *IfcSpace* and *IfcSite*. The other two extensions are less complex and contain a total of 11 entities including procedure, task and work plan entities.

Resource Layer: The entities of the resource layer contain support objects that are not facility specific. These include definitions such as geometry, quantity, date and time. All the information contained in a *geometric data model* is found in the resource layer. These resources are generic to objects and provide support information to higher level objects, some of which were adapted from the STEP standard.

Due to the large number of entities in IFC it is difficult to provide a simple and complete example of an IFC model of a facility. Appendix A features a more detailed explanation of an IFC model and the basics on how geometric properties are associated with the facility entities. Our discussion will now turn to an examination of the benefits of *building data models* over *geometric data models*.

3.2.1 IFC Sample

To demonstrate the hierarchical nature of the IFC architecture and the entities we will discuss an example of a small facility. The small facility is the one room example from figure 2.5 and has been represented using IFC entities in Figure 3.3. The figure utilizes a simplified EXPRESS-G notation to represent the entities.

The facility begins with the abstract entities of the core layer and moves to the interoperability layer to create more specific objects. The objects between the root and the wall represent the abstract concepts required to instantiate a wall object and provide the set of properties that the wall will inherit when it is created.

In this example we can observe that even in the case of a small facility numerous entities must be present. Contextual information is available but must be linked to the entities accordingly to provide meaning.

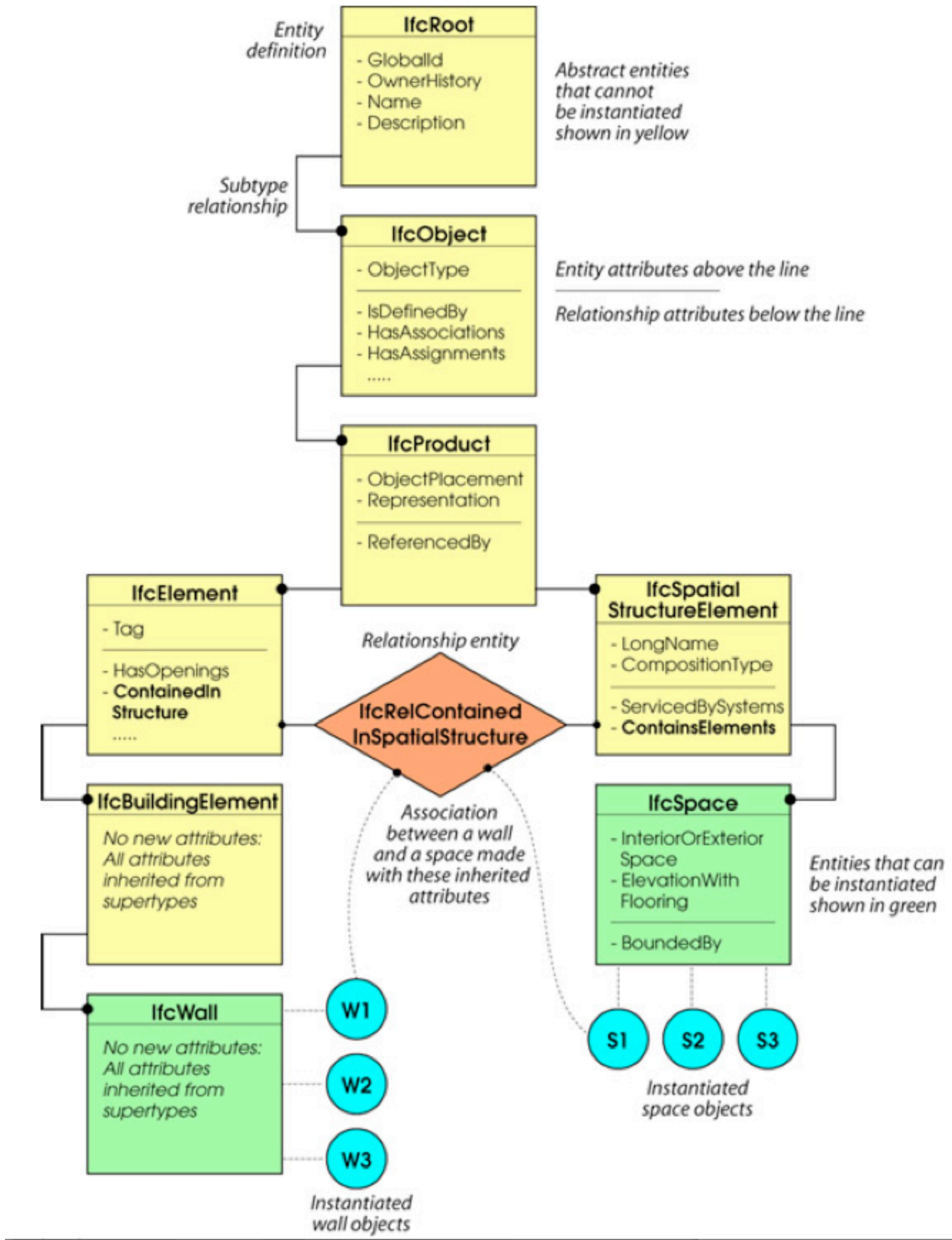

Figure 3.3: IFC Structure Example (Khemlani, 2004)

3.2.2 Relationships and Property Sets

Hierarchical relationships are the relationships between the entities in the IFC architecture. *Relationship entities* are objects used to create relationships between building elements outside of the hierarchical relationships. In the example from the figure 3.2, the wall and the space are not hierarchically related, they are related through the use of a *relationship entity*. The *IfcRelContainedInSpatialStructure* entity is introduced to provide that relationship. The indirect nature of this relationship implies that the objects can be combined in multiple configurations for different applications.

The properties associated with an object fall into two categories, property sets and attributes. Attributes are properties common to all instances of an entity. Property sets are optional associations that may or may not be associated with an object; they are included in order to represent specific requirements such as local regulations. Property sets provide additional flexibility as the user may include required property sets or define their own to meet non-platform requirements.

3.3 IFC and Workflow

The combination of IFC and workflow presents some challenges as workflow is not a core component of the specification. There are elements that appear similar to workflow concepts in the IFC specification, but they are project management elements used in the construction process, not in the future use of the facility by its occupants. In order to ascertain how workflow can be combined with IFC, the existing entities are discussed to determine if they are applicable. The first extension we will examine as a suitable candidate for representing a workflow in IFC is the process extension.

3.3.1 The Process Extension

The process extension elements were created in order to define a construction schedule task list. It contains 7 entities and 2 entities whose descriptions are summarized in table 3.1 as taken from the IFC model guide (IFC, 2004).

The abstract entities may appear suitable for workflow representations, however they

Table 3.1: IFC Process Extension

Entity	**Description**
IfcProcedure	Identifiable step to be taken within a process that is considered to occur over a non-measurable period of time
IfcRelAssignsTasks	Relationship class that assigns an *IfcTask* to an *IfcWorkControl*
IfcScheduleTimeControl	Captures the time-related information about a process
IfcTask	Identifiable unit of work to be carried out independently of any other units of work in a construction project
IfcWorkControl	Abstract supertype which captures information that is common to both *IfcWorkPlan* and *IfcWorkSchedule*
IfcWorkPlan	Represents work plans in a construction or a facilities management project
IfcWorkSchedule	Represents a task schedule in a work plan, which in turn can contain a set of schedules for different purposes
IfcProcedureTypeEnum	Defines the range of different types of procedure that can be specified
IfcWorkControlTypeEnum	enumeration data type that specifies the types of work control from which the relevant control can be selected

provide no means for physically representing the workflow in the model. They may still be used at a later date for storing workflow information, but our focus is on entities with physical representations.

3.3.2 Model Development

Although there is a large pool of possible entities available in IFC there is only a small number that are suitable for use in representing the physical components of a workflow. The context of the workflow contains many dimensions each with their own set of unique properties that should be catalogued separately. At this stage there is no set of unique IFC entities that can be used to accurately describe the contextual requirements of a workflow; there are elements in different layers that can be used but this is a patchwork solution.

Using IFC to fully define context would require the creation of a new group of building data elements. The barriers to this approach include the alteration of a data standard with non-standard elements and the lack of enumeration of all the information that relate the two entities. This is partially due to the lack of a formal description of all the contextual dimensions as they relate to workflow.

At this point we are examining the relationship between the spatial contextual dimension and the workflow which requires IFC entities that describe the 3-space geometric components of the workflow and space. We are operating under the assumption that any additional contextual information is stored in either the definition of the workflow on the context and the the geometric components are sufficient for relating the two.

IfcSpace and *IfcPath* are entities with physical representations that may be used for workflow. *IfcSpace* can specify the activity center of the workflow and the pathways between activity centers are specified using *IfcPath*. They are also abstract and can be applied to describe the contents of the facility in which workflows occur.

3.4 Prototype Modeling

The facility used for the prototype was the floor-plan of the reception area at the diagnostic imaging department at Grand River Hospital (GRH) as shown in Figure 3.4. It was selected in part because it has been previously studied: the workflows involved in the inpatient booking process and had been well documented.

The workflows consist of a series of process maps (Appendix B) that were created by a former student Weizhen Dai and were discussed in his thesis (Dai, 2005). Our extension will be to create the workflows as objects in an IFC model and to tag the elements of the workflow to corresponding IFC entities. Each workflow entity will be assigned to a specific space or path entity on a one-to-one relationship.

The facility layout was privided as a CAD file, not an IFC model. In IFC, geometric information is associated with building elements first through abstract facility objects in the core layer, and then the instantiable elements in the interoperability layer. This makes direct conversion from geometric information impossible. Therefore the inpatient booking area was replicated with ArchiCAD in order to replace the CAD layout with IFC entities.

Figure 3.4: GRH Diagnostic Imaging Layout

The ArchiCAD 2D and 3D models are shown in Figure 3.5.

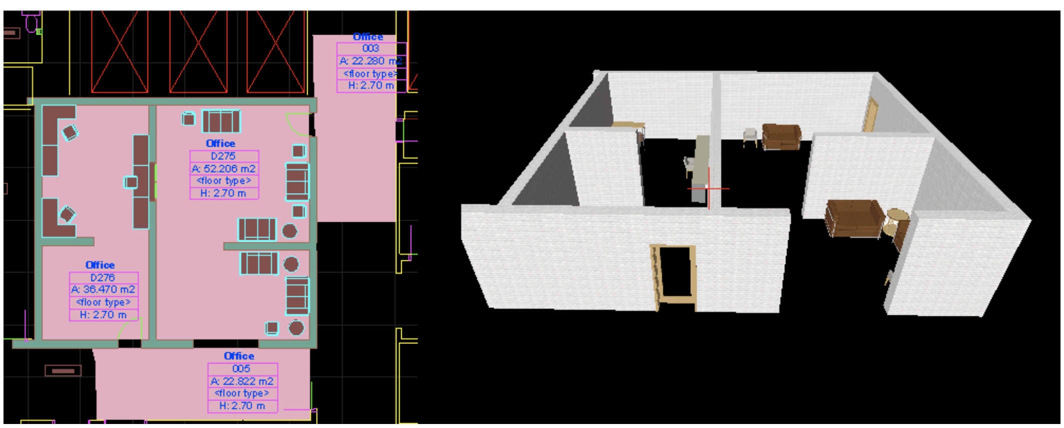

Figure 3.5: IFC Model of DI Reception in 2-D and 3-D

In our new layout, the activity centers of the workflows are marked as *IfcSpaces* and the routes with *IfcPath* entities. Each space is treated as an activity center with paths used as connecting routes between the centroids of the spaces. The paths between activity centers are straight lines that may pass through physical objects such as walls. At this stage we are using manually generated workflows, therefore we also use manual reconfiguration of the pathways to solve this problem.

The *IfcPath* entity is defined as a topological entity consisting of an ordered collection of oriented edges (IFC, 2004). Using this definition a single workflow route can be an *IfcPath* element that would comprise of multiple edges. As a collection of edges, the routes are 1-dimensional entities that are to be used to describe the transport of 3-dimensional objects. This does not agree with our definition of a coupled system as the dimensions of the routes and contextual dimension differ.

3.5 Chapter Summary

IFC was introduced as a *building data model* and a means of representing the physical environment. It provides a more detailed representation of the facility than *geometric data models*. Based on these findings we discussed an initial model for the integration of workflows and IFC.

In this implementation, the workflow routes are represented as sub-elements of the space; the routes between the activity centers (*IfcPath* entities) are 1-dimensional objects in a 3-dimensional space. It followed an approach that contradicted the analysis provided earlier in this thesis. In our problem statement, we noted that workflows are defined within a context and inherit its dimensions. The *IfcSpace* element as a representation of workflow activities has the same dimensions as the 3-space of the spatial contextual dimension, but the *IfcPath* does not. The transport component of a workflow between activity centers, such as patient transport, exists in 3-space with objects of various sizes and speeds.

In our search for a workflow representation we adapted existing classical techniques to provide a candidate solution. Given that this solution is not adequate we will be re-visiting our workflow representation within IFC.

Chapter 4

Workspace Design

Chapter 3 concluded with concerns over the representation of workflow's in IFC models using the space and path entities. In chapter 4 we will be addressing these issues and developing a new representation of workflow in IFC.

4.1 Defining a Solution Space

The use of *IfcSpace* and *IfcPath* was due to the lack of workflow primitives available in the IFC specification and mirrored classic workflow representation techniques. Before applying a different set of entities to represent workflows we will consider the cause for the incompatibility. As stated in chapter 1, a workflow exists within a context and inherits its dimensional characteristics. The characteristics of the spatial dimension is 3-space and the workflow representation should possess similar dimensions.

4.1.1 The Concept of Work Available Space

In our study of workflow context we stated that context did not define the workflow, but that it provided an environment in which the set of possible workflows existed. In the spatial dimension the contextual boundary is the physical objects and the space in which workflows occur is all the unused space. The space defined by the contextual boundary of a facility will be referred to as the *work available space* and is the projection of the unused space in a facility onto an abstract 3-space. Figure 4.1 uses a test facility to demonstrate the principle of *work available space*.

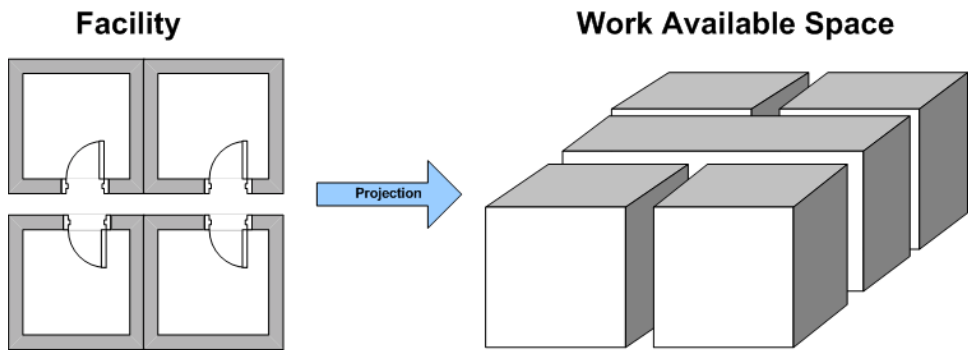

Figure 4.1: Work Available Space Example

This is a philosophical departure from prior definitions. The IFC entities that represent solid objects are no longer the focus. They provide contextual boundaries for the workflows in the space, but are not a part of the workflow description except through inheritance and relationship entities.

4.1.2 The Concept of Work Space

In order to create a dimensionally comparable entity to *work available space* we take spatial requirements of a workflow and place them onto an abstract 3-space. Projecting it preserves the workflow as a multi-dimensional entity and utilizes the components that are relevant to the spatial layout. This abstract 3-space can be visualized as a blank canvas with objects based on the size requirements of process activities: this is the workflow's *workspace*.

Figure 4.2 is an example of extracting the workspace from a workflow. The spatial requirements reflect the minimum amount of space required for each process element. The orientation at this point is arbitrary, as the workflow is not bounded by any physical constraints. At the projection stage, the workflow can be visualized as what it would look like in a real world setting without the limitations imposed by a facility. Activity centers are defined based on 3-dimensional geometry, and transport is also defined using the same

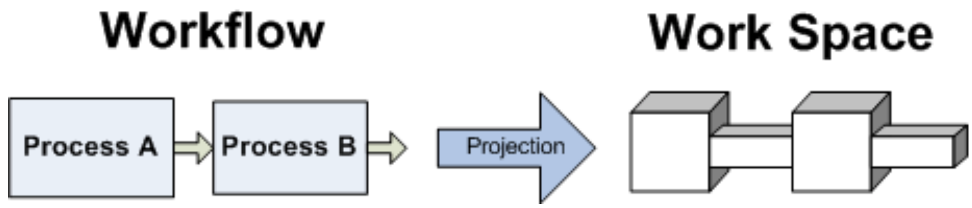

Figure 4.2: Work Space Example

characteristics. In the *workspace* of the workflow, the routes are dimensionally equivalent to the activity centers.

4.1.3 Understanding the Projections

Our study of workflows and facilities is now the study of projections of their physical components onto a subspace. Representations of a workflow in a facility becomes the assignment of one or multiple *workspaces* to a *work available space*. Our next challenge is to determine how to combine the two projections together to form a single cohesive representation. This will be defined as the zoning process. An example of the combination between *work available space* and *workspace* and their projections can be found in figure 4.3.

4.2 Zoning

In this section we will be generating a zoning method that works with our definition of *workspace* and *work available space*. Zoning is the process that we utilized tacitly through the application of *IfcSpace* and *IfcPath*. The facility was zoned into functional and non-functional blocks to represent the workflow and unused space. In this section we will take a workflow and an associated space for the process and combine them to form a workspace-workflow entity.

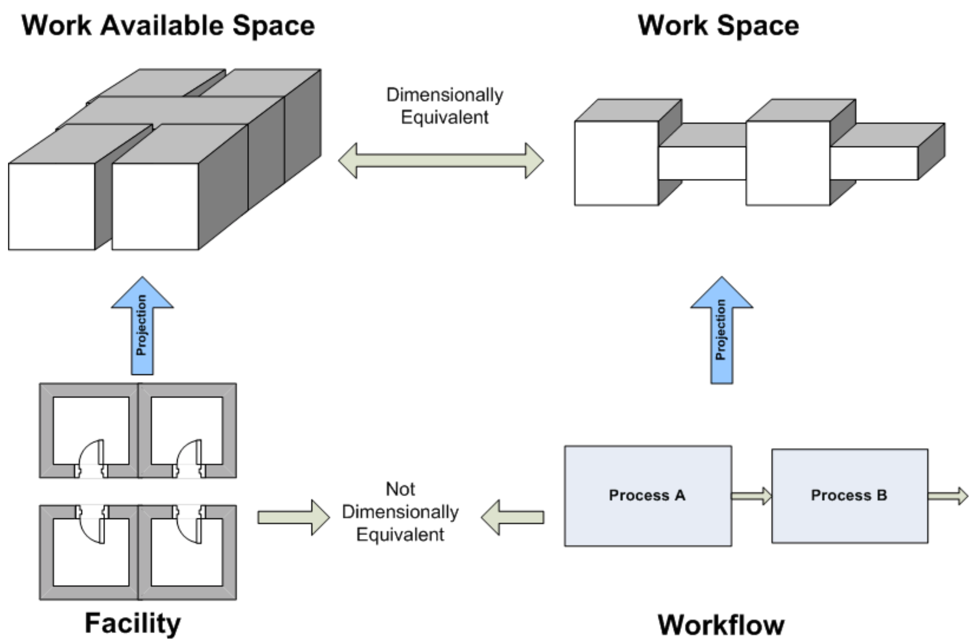

Figure 4.3: Relation of Projections

4.2.1 Work Available Space

The *work available space* is defined as the unused space of a facility, a concept with which we are already familiar with in IFC. Zoning *work available space* using IFC elements is done with the *IfcSpace* and *IfcZone* entities. The unused space in rooms is defined as an object using the *IfcSpace* entity based on functional blocks of space.

The *IfcZone* element is a macro object that is defined in the IFC specification as a collection of *IfcSpaces*. *Work available space* in IFC can be defined by combining the *IfcSpaces* into *IfcZones*. For the duration of this work, reference to a representation of *work available space* will be referencing an *IfcZone* entity. The use of the word zoning refers to the type of workflow activity that occurs in a space, not the *IfcZone* element.

4.2.2 Workspace

There was little direction present in the literature for defining the zone types for workflows. One example was found in a paper on multi-criteria layout planning (Jacobs, 1987). This paper discussed the division of space in facilities layout problems based on the variable domain array method. This method divided the office space/facility into equally sized blocks and defined the space in terms of available space, dead space, solid space and circulation space. The analogy to our method is available space represents the *work available space* and dead space is the boundaries defined by the facility solid objects. Solid space and circulation space are the space utilized by the workflow. A discussion on the merits of this approach and the concerns with respect to workflow is available in appendix C.

At this stage we will maintain that space can be assigned as either activity, transport, waiting or unused space for workflows. Dead space is defined by IFC building objects and is outside our definition of *work available space*. A *workspace* is defined in IFC by assigning a type of zone to each space and linking it to a *workspace* element. Each activity or process element is assigned to a unique *work available space* object. Multiple routes can be assigned to each transportation space as they are shared between *workspaces*.

4.3 Chapter Summary

In this chapter we examined the nature of the representation of workflow in the spatial contextual dimension. The concepts of *workspace* and *work available space* were defined in order to created workflow and context outside of the framework of the facility.

The zoning process was created to combine the projections together. The functional blocks of space from the facility were assigned to *workspace* elements based on the type of activity that occurs in the zone. We can now revisit our example from Chapter 3 and to include the zoning process.

Chapter 5

Prototype Design

In this chapter we will be building on the prototype discussed in chapter 3 by including the zoning process developed in chapter 4. Extensive testing of this model would have required the creation of an expert system to test the effects of applying this contextual knowledge in the design process. Creating such a system would require the formalization of the links between the workflow and the environment to determine what information is applicable. Pursuing this avenue of research proved to be extremely challenging, as such the scope of this work was limited. This is intended as an analysis of the methods of representing context and workflow, and understanding the need for a philosophical shift in their definitions. The next step is to define a method that would be far more detailed than previous efforts and understanding how it could be combined with workflow to create a new model for analyzing this interaction.

5.1 Prototype System Design

From a system perspective, we have an IFC model that contains the contextual description of the environment, and workflow information stored separately. There are currently no applications available that can be used to combine simulation and IFC workflow information, therefore we were required to find a way to combine the two.

The IFC model was kept in its standardized data format, although the XML definition was used to create a version of the data more accessible to other applications. We are operating under the assumption that facility is not subject to change at this point and that the IFC model is read-only data. Workflows can be stored in many formats, many of which were described in Chapter 2, but for our sake we will be storing them within a database.

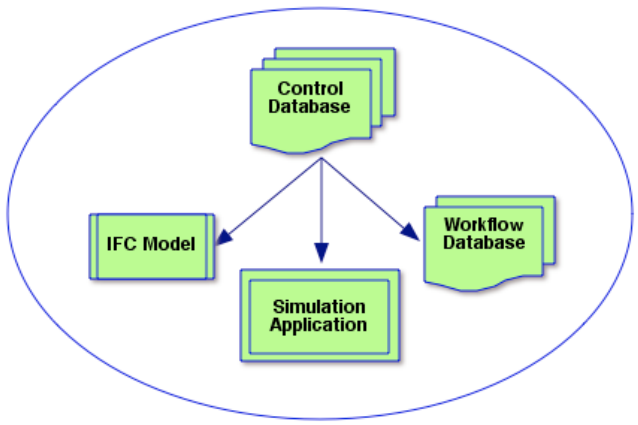

Figure 5.1: Prototype System Diagram

Figure 5.1 is a system diagram relating the components of the prototype system and the associated data sources. The control database was created to store the information required for the data sources to interact. This includes the information attained from the zoning process that links the workflow to the IFC model.

5.2 Zoning Implementation

We build on our example from Chapter 3 by zoning the space using the rules described in Chapter 4. The reception area was divided into functional blocks of space based on the requirements of the workflow (Fig. 5.2).

The *work-available spaces* are defined in the IFC model as *IfcSpace* objects. What is not stored in the IFC model is the information on the zoning of these spaces, which exists outside the current IFC definition. This information is stored in the control database as each space is zoned with each workflow activity and transport connection linked to one of these spaces.

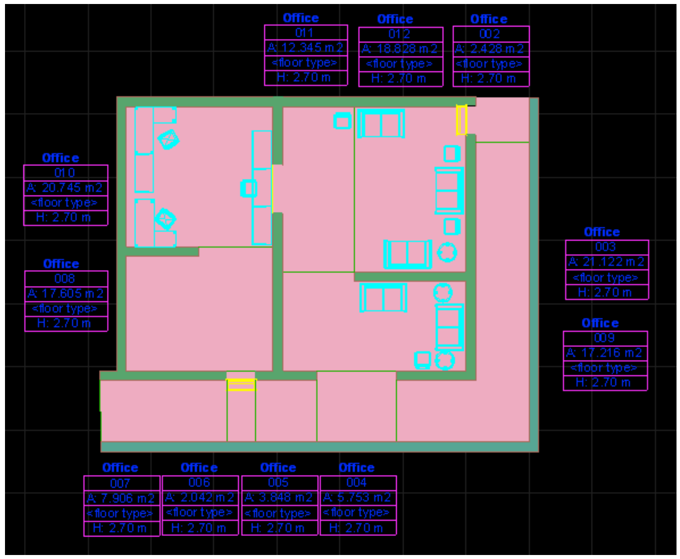

Figure 5.2: Reception area divided into *IfcSpaces*

The routes between activities have a many-to-one relationship with space; spaces may be associated with multiple routes and routes may pass through multiple spaces. Space is designated by default as *unused space* and is zoned as *waiting space* as required. Information such as the occupancy of the *waiting space* is stored in the IFC model and is not re-listed.

Workspace is defined by assigning a zoning type to each of our spaces. In this example we use the same workflows and spatial division used in our example from chapter 3. The difference being that some of the spaces were divided into sub spaces to reflect the different zoning requirements. Using this method spaces are not by default assigned as *activity space*, but are zoned based on workflow requirements. In figure 5.3 the space has been zoned and colour coded according to the zone types. The workflows associated with inpatient booking are all related to 3-dimensional spaces.

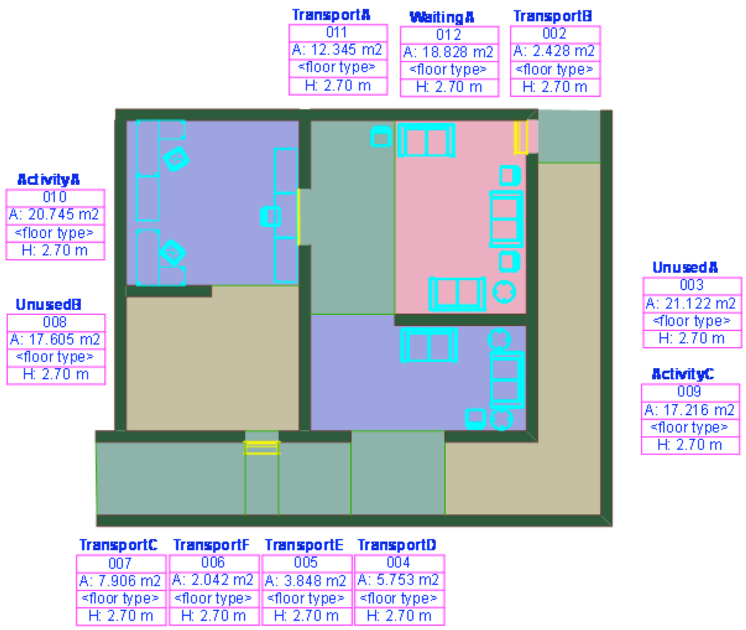

Figure 5.3: Zoned reception area

5.3 Implementation Procedure

With the development of a method of representation we can now turn to visualizing the workflow in action. The visualization process will ideally allow us to step through the workflow and determine how it interacts with the environment. To achieve these goals we will be utilizing a simulation application.

5.3.1 IFC and Simulation

IFC simulation applications exist, however as outlined in chapter 3, they are not suitable for workflow simulations. Arena, an existing workflow simulation application was selected to provide a means for simulating the workflow. Workflows are created in Arena as processes with each process element defined quantitatively (arrival time, waiting time, etc.) in order to create a simulation to demonstrate the expected behaviour of the system. The results of these simulations can then be used to examine workflows in action and help determine if there are any process inefficiencies present in the system.

Arena was selected for simulation purposes for several reasons. It is a robust simulation application with MSDA standard scripting capabilities and the ability to import visual layouts from several applications. Arena is composed of two primary engines, a simulation engine and a visualization engine. The workflow and its elements are entered in the simulation engine and the IFC layout into the visualization engine.

Arena requires that the workflow process elements are defined separately from the visualization component. The basic *process* and *link* Arena object blocks are adequate representations of the standard workflow activity and route objects used in our workflow descriptions. These are simulation elements; they do not visualize the workflow, they are used to provide a description of the worfklow.

At this stage the workflows exist in a classical process map representation in the Arena simulation engine. The workflow is de-coupled from the facility and is a representation of the process elements.

5.3.2 Facility Input

Arena allows for visual layouts to be imported directly in several formats including DXF and image file formats, however IFC models are not one of them. The facility representation was imported into Arena utilizing a script to redraw the basic building objects. The first step was to parse the IFC code to extract the basic 2-D layout information based on geometric relations.

Once the IFC model had been parsed for the geometric components of the walls as basic structural elements, they were re-drawn in Arena. Creating the workflow in the visualization engine requires some additional steps. This was accomplished by associating the centroid of each *IfcSpace* with a station object from Arena. The *station* and *route* objects in Arena are utilized as the workflow elements in the visualizations to tie the two engines together. Once associated with a process, the *station* object acts as an anchor for graphic objects in the visualization engine. The routes are set from centroid to centroid of the spaces in between process elements in order to connect the *stations* together.

At this stage we have defined the workflow within Arena in what appears to be a de-

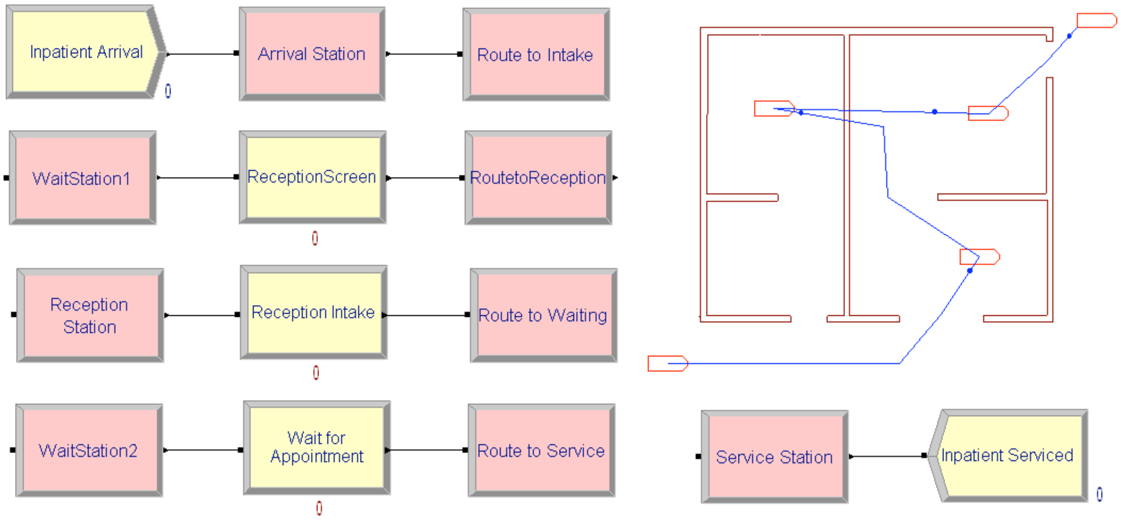

Figure 5.4: Arena Workflow

coupled system. Through the use of a control database and the zoning process we have the ability to link the workflow information and the simulation data to the IFC model. The next phase of our study is to understand how to leverage this step towards the creation of a coupled system.

5.3.3 System Analysis

At this stage, Arena provides the capability to visualize a workflow, but does not provide a coupled system. The approach of re-drawing the facility is no different from previous implementations. The path to a coupled system lies in the creation of links between the simulation objects and the IFC model. In order to determine the possible links between the workflow and the environment we will discuss properties and objects that relate the two.

One property in IFC that can be associated with a space is its occupancy limit, a value that may be based on regulations (fire code, etc.) or room size. The occupancy limit is stored in the IFC model of the space as the *Pset_SpaceOccupancyRequirements* which is a property set definition applicable to the *IfcSpace* and *IfcZone* classes.

Upon completion of several simulation runs of the workflow under study, one can extract the maximum and expected occupancy of a room from Arena by examining the maximum and average queue size of a process. When the simulation is run, statistics are kept with respect the limit values of the queue for each process element. Using our example of occupancy of a room, we could compare a queue size for a process (e.g. reception waiting room) with the simulation values in order to determine if a violation can be expected to occur.

In this example we are extending the simulation data to relate it to the design-aspects of the facility. It is taking the simulation data and utilizing the properties and attributes specified in the IFC model, a data set that was not previously available.

5.4 Chapter Summary

The use of the zoning strategy has not lead to a representation of workflows in which the workflow elements possess the same dimensions as the contextual environment. A prototype was developed to demonstrate that simulation data could be related to the facility to create a coupled system. This information, although gained manually, is available in a machine interpretable format.

The creation of a coupled system is the combination of the workflow, IFC and simulation into a single joint system. Only one example of coupling between the context and the workflow was presented. Information on identifying and describing these links in a machine interpretable format is unavailable at this stage. What it does present is an example moving towards a coupled system that may take advantage of the links to contextual information available in an IFC model.

Chapter 6

Conclusions and Discussion

6.1 Conclusions

Classic workflow representation techniques provide the ability for a designer to step through workflows. This commonly manifests itself in the ability to traverse flowcharts or process maps. In reality workflow occurs in a spatial environment that has definable properties (room capacity, hallway flow rate, etc.) that can impact its execution. This information is not available in current representation techniques, and would be of use in analyzing workflow execution via simulation (e.g., to determine queue lengths and relate it back to room capacity) in order to optimize it.

Given this, we analyzed the existing means of workflow representations to determine if any systems met the above criteria. Existing systems were found to be de-coupled systems where the workflow and the description of environment were tacitly connected.

We developed an approach where workflow descriptions are projected into a coupled spatial environment. This has involved the selection of a leading object-oriented representation of spatial environments (IFC). The introduction of IFC provided a means for the inclusion of contextual information into workflow representations and visualizations. The objects and the unused space in a facility are well defined with associated property sets. The relationship between the workflow and the contextual environment is formed by assigning the workflow to a discrete spatial object. Once it is assigned it inherits the properties of that space.

We then created a zoning process to visualize the workflow with the spatial environment. We identified the types of space utilized by workflow, the relationship between space and workflow and the properties unique to workflow. The spaces defined in IFC represented the *work available space*, and the assignment specified by the workflow corresponded to the *workspace* concept. This guideline was used as a method to combine workflow within the visual IFC model of the facility.

In order to test this coupled system concept and the zoning process a prototype was created using and IFC model and a workflow simulation application. It demonstrated that the two can be combined, but that there are several complications in this implmentation. It requires a better understanding of the all the relationships between workflow and the contextual environment. The complete list of these relationships are not a part of this work and are required for proceeding further with this approach.

6.1.1 Limitations of this Work

The focus of the work was on a proof of concept work for the representation and visualization of workflow, not on developing a full-scale application. The zoning process provides a means for 3-dimensional representations of workflows, but the extensions of the buffer concept and bandwidth of a transportation space require further discussion.

These limitations are due to a lack of formalization. The work is rooted in an analysis of the nature of context and workflow and the prototype is an attempt to put the theory into practice. The flaws in the small scale model provide a platform for future work in this field.

6.2 Suggestions for Future Research

6.2.1 Implementation on a Larger Scale

In its current form, the workflow definition is a database version of a process map. This approach allowed for modifications required by *workspace* and *work available space*. A larger scale implementation would likely require a standardized workflow database interoperable with IFC as well as other workflow applications.

We have yet to create a coupled system, we have been building on the concept of a joint system with a more detailed independent definition of the contextual environment. The next step would be to formally develop a joint system that makes use of IFC for the evaluation of workflows to determine the benefits gained from this new approach.

6.2.2 IFC and Simulation

From a simulation perspective there is some interest in determining a more complete list of relationships between simulation/workflow objects and the environment. The example used was constructed and formalizing these relationships may require considerable work. Relating the maximum queue size to the occupancy of a room is one concept, but understanding how to codify the relationships is a separate matter. One of our objectives was to improve the machine processing capabilities of workflows and in order to do so, these relationships need to be formalized.

The integration of IFC and Arena was forced at best. It would be ideal to create a 3-D workflow simulation application that could work directly with IFC models. At this time there is no evidence that such an application is under development.

6.2.3 IFC and Facility Design

The literature review identified facilities layout as an example of the combination of existing research of contextual properties and workflow. Further discussion was omitted from the prototype model that instead focused on the impact of simulation and contextual information.

It also remains to be seen whether or not this representation of a contextual dimension would be suitable for expert systems that combine multiple solution techniques. The use of the IFC *building data model* offers an explicit definition of context that has not been used in existing expert systems. Determining if this data could be leveraged may be valuable in further research.

6.3 Final Thoughts

We have yet to discuss definitions of context and the creation of coupled systems for the other contextual dimensions. If the contextual dimensions are related to one another we may need to define them prior to formalizing the relationships between workflow and context. Using our waiting room example, the size of the room may be affected by organizational goals or procedures which may create a limit on its capacity.

The concept of a coupled system is an intriguing one that would appear to unify different avenues of research. By combining them together we could leverage their benefits to improve facility design and workflow evaluation. The use of *building data models* to represent workflows and a contextual dimension provide a stepping stone towards this goal.

Appendix A

IFC Six Room Example

This appendix will discuss the IFC code for a six room facility as shown in figure A.1. The full IFC/ifcXML code for this example has not been included in its entirety due to its length. Printouts of the code were 144 and 1290 pages respectively for the IFC and ifcXML code.

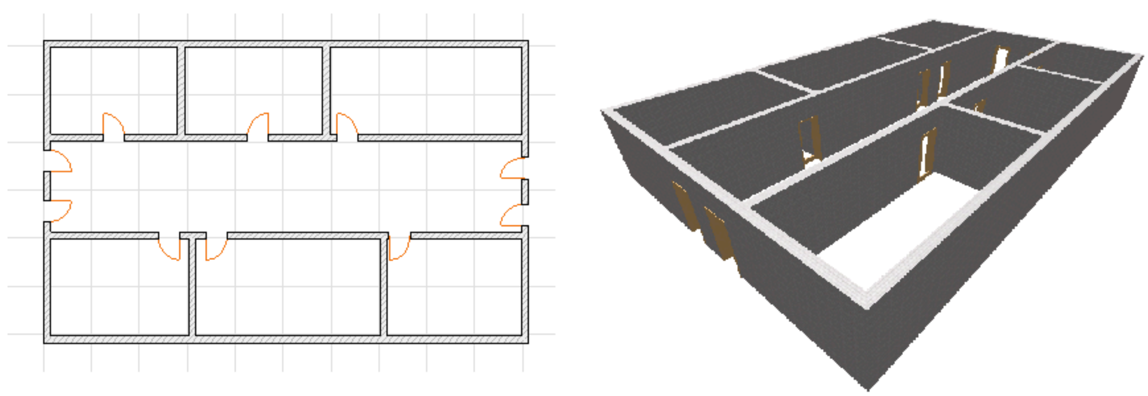

Figure A.1: Six Room Facility

Part of the reason for this length is the volume of entities required for the definition of a simple facility as outlined in the criticisms in the literature of IFC. Prior to the instantiation of a given object all the super-entities need to defined. These super-entities are defined by an inheritance graph for each IFC object. The inheritance graph for the *IfcSpace* is listed below:

```
ENTITY IfcSpace;
ENTITY IfcRoot;
GlobalId :IfcGloballyUniqueId;
OwnerHistory:IfcOwnerHistory;
Name:OPTIONAL IfcLabel;
Description:OPTIONAL IfcText;
ENTITY IfcObjectDefinition;
INVERSE
HasAssignments:SET OF IfcRelAssigns FOR RelatedObjects;
IsDecomposedBy:SET OF IfcRelDecomposes FOR RelatingObject;
Decomposes:SET [0:1] OF IfcRelDecomposes FOR RelatedObjects;
HasAssociations:SET OF IfcRelAssociates FOR RelatedObjects;
ENTITY IfcObject;
ObjectType:OPTIONAL IfcLabel;
INVERSE
IsDefinedBy:SET OF IfcRelDefines FOR RelatedObjects;
ENTITY IfcProduct;
ObjectPlacement:OPTIONAL IfcObjectPlacement;
Representation:OPTIONAL IfcProductRepresentation;
INVERSE
ReferencedBy:SET OF IfcRelAssignsToProduct FOR RelatingProduct;
ENTITY IfcSpatialStructureElement;
LongName:OPTIONAL IfcLabel;
CompositionType:IfcElementCompositionEnum;
INVERSE
ReferencesElements:SET OF IfcRelReferencedInSpatialStructure FOR
RelatingStructure;
ServicedBySystems:SET OF IfcRelServicesBuildings FOR RelatedBuildings;
ContainsElements:SET OF IfcRelContainedInSpatialStructure FOR
```

```
RelatingStructure;
ENTITY IfcSpace;
InteriorOrExteriorSpace:IfcInternalOrExternalEnum;
ElevationWithFlooring:OPTIONAL IfcLengthMeasure;
INVERSE
HasCoverings:SET OF IfcRelCoversSpaces FOR RelatedSpace;
BoundedBy:SET OF IfcRelSpaceBoundary FOR RelatingSpace;
END_ENTITY;
```

It begins with a header which contains file metadata including description, name and schema as specified by the ISO-10303 definition. The IFC entities are listed in the *DATA* section which upon termination represents the end of the file. An abbreviated version of the the six room example has been included below as an example of the format of the data.

```
backslash
ISO-10303-21;
HEADER;
FILE\_DESCRIPTION(('ArchiCAD 10.00 Release 1 generated IFC file.','Build
Number of the Ifc 2x2 interface: 55377 (14-11-2006)X0A'),'2;1');
FILE\_NAME('C:\\ Documents and Settings\\Dave\\My Documents\\ex\\code
\\IfcTest.ifc','2007-08-24T00:37:23',('Architect'),('Building Designer
Office'),'PreProc - EDM 4.5.0033','Windows System','The authorising
person');
FILE\_SCHEMA(('IFC2X2_FINAL'));
ENDSEC;

DATA;
#1= IFCORGANIZATION('GS','Graphisoft','Graphisoft',$,$);
#5= IFCAPPLICATION(#1,'10.0','ArchiCAD 10.0','ArchiCAD');
#6= IFCPERSON($,'Undefined',$,$,$,$,$,$);
#8= IFCORGANIZATION($,'OrganizationName',$,$,$);
#12= IFCPERSONANDORGANIZATION(#6,#8,$);
```

```
#13= IFCOWNERHISTORY(#12,#5,$,.NOCHANGE.,$,$,$,1187930241);
#14= IFCSIUNIT(*,.LENGTHUNIT.,.MILLI.,.METRE.);
...
...
#12356= IFCRELAGGREGATES('1kwdRMVkHAp8OmeACSlerA',#13,
'ProjectContainer','ProjectContainer for Sites',#42,(#51));
ENDSEC;

END-ISO-10303-21;
```

IFC in the EXPRESS syntax is defined by a sequence of lines of code in which each line represents an IFC entity. Each line will reference other lines of code by line number to establish a relationship. Exceptions to this rule do exist for highly granular objects, such as *IfcCartesianPoint*, and highly abstracted entities such as *IfcOrganization* which is a root object.

We will use an example to explain the hierarchy of objects for an *IfcSpace*. The spaces are defined for each room and the hallway as the usable space of the facility. The space under examination is the space represented in the upper left room and is the rectangular area defined by the interior of the room. Please note that the EXPRESS syntax is similar to Pascal and the $ operator represents an unset value. The entity is defined using the following line of code:

```
#546= IFCSPACE('1Lx_Ye9VL2kAdmzAWRNyPX',#13,'001',$,$,#543,#537,'Office',
.ELEMENT.,.INTERNAL.,$);
```

Of these values 001 and Office represent the name given and the type of space as defined in its creation in ArchiCAD. The first value is its unique ID while the remaining set values describe its relation to the rest of the facility. #13 is a reference to the *IfcOwnerHistory* entity which is used to define the owner, creator and last known person to modify the element. #543 and #537 are used to represent the geometric properties of the space stored in separate lines of the data file. Lines #543 and #537 are included below for reference purposes:

```
#537= IFCPRODUCTDEFINITIONSHAPE($,$,(#526,#533));
...
#543= IFCLOCALPLACEMENT(#72,#542);
```

The geometric definition of the object is divided into two components, the definition of its shape and the placement with respect to the other objects. In our definition of the space for this example we did not associate it with other facility elements (walls etc.) or specify any property sets. The placement of the space is defined by the following lines of code:

```
#28= IFCDIRECTION((1.,0.,0.));
#30= IFCDIRECTION((0.,1.,0.));
#32= IFCDIRECTION((0.,0.,1.));
...
#540= IFCCARTESIANPOINT((1960.0584,13679.234,0.));
#542= IFCAXIS2PLACEMENT3D(#540,#32,#28);
```

In this definition the placement of the space defined as a cartesian point on the layout and the reference directions. The definition of the product shape is more complex then that of the placement. The definition of the geometry the space is divided into two components: the boundaries on the total space, and the use of the space.

The boundary of the space is defined by a bounding box. A bounding box is a box used to limit the dimensions of a solid object. The parameters of the bounding box are a corner and a length definition in each of the 3 axes. An example of a bounding box is found in the following lines of code:

```
#530= IFCCARTESIANPOINT((0.,-5389.4768,0.));
#532= IFCBOUNDINGBOX(#530,3916.1964,5389.4768,2700.);
#533= IFCSHAPEREPRESENTATION(#144,'IAI','BoundingBox',(#532));
```

In this example the space in question has dimensions equal in size to the bounding box, if this were not the case the other half of the definition would apply. For shapes that are not cuboid they still fit in a bounding box but can be defined as a sub-entity of the space defined by the bounding box.

This concludes our example on the representation of a instantiated IFC entity with respect to its geometric properties. This example will be referenced later in the discussion on the extraction of geometric properties from an IFC model.

Appendix B

Workflow Examples

These workflows of the inpatient booking process at Grand River Hospital were developed by Weizhen Dai in 2004. They were created as a part of his graduate research into query-based workflow process dependancy.

These workflows have been used as samples in conjunction with the layout of the facility provided. They contain several steps that occur in the same spatial location. We combined groups of activities together if they were found to occur in the same space.

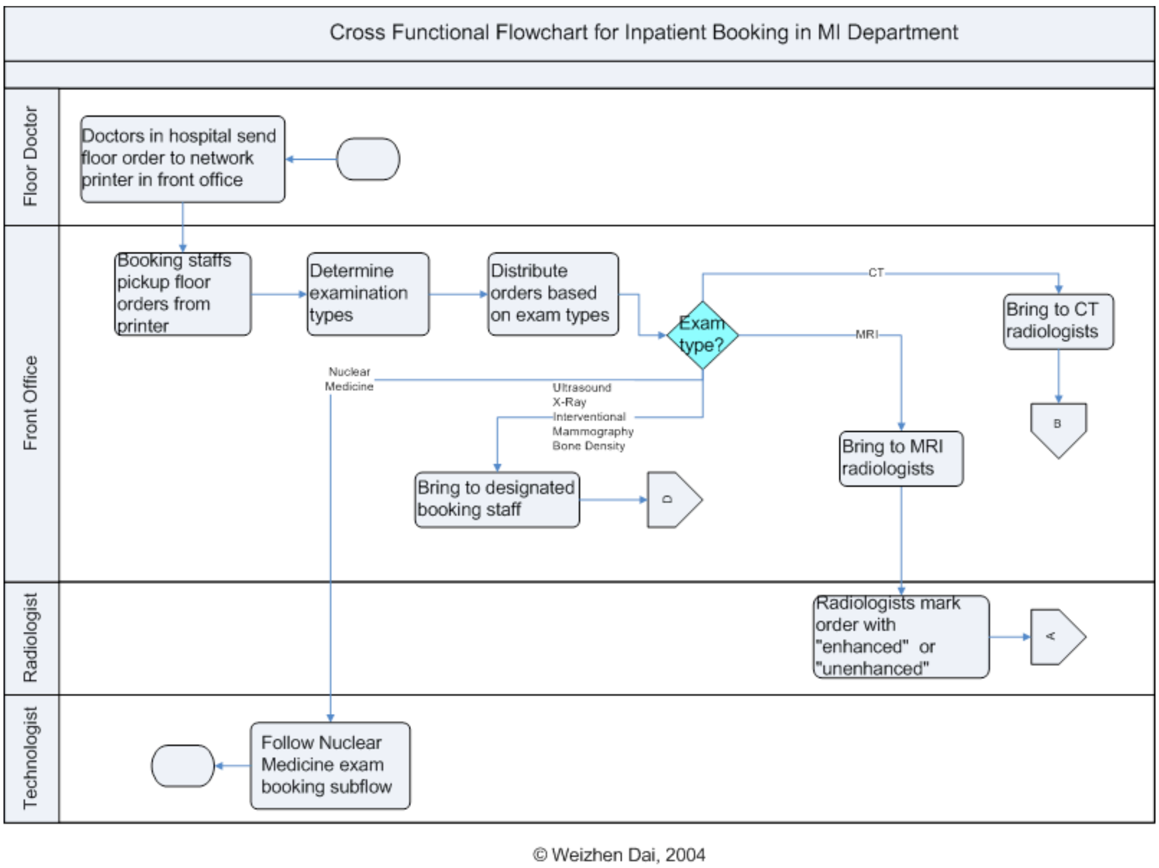

Figure B.1: Workflow: Page 1

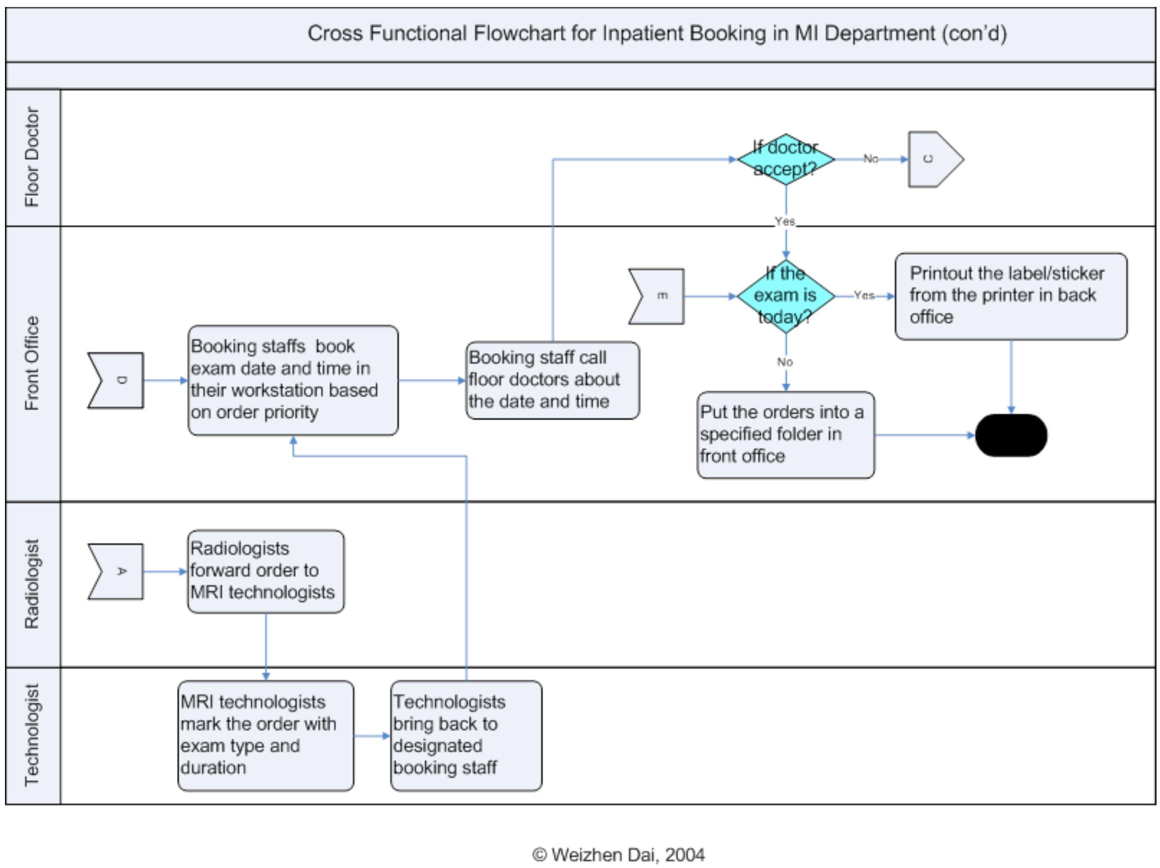

Figure B.2: Workflow: Page 2

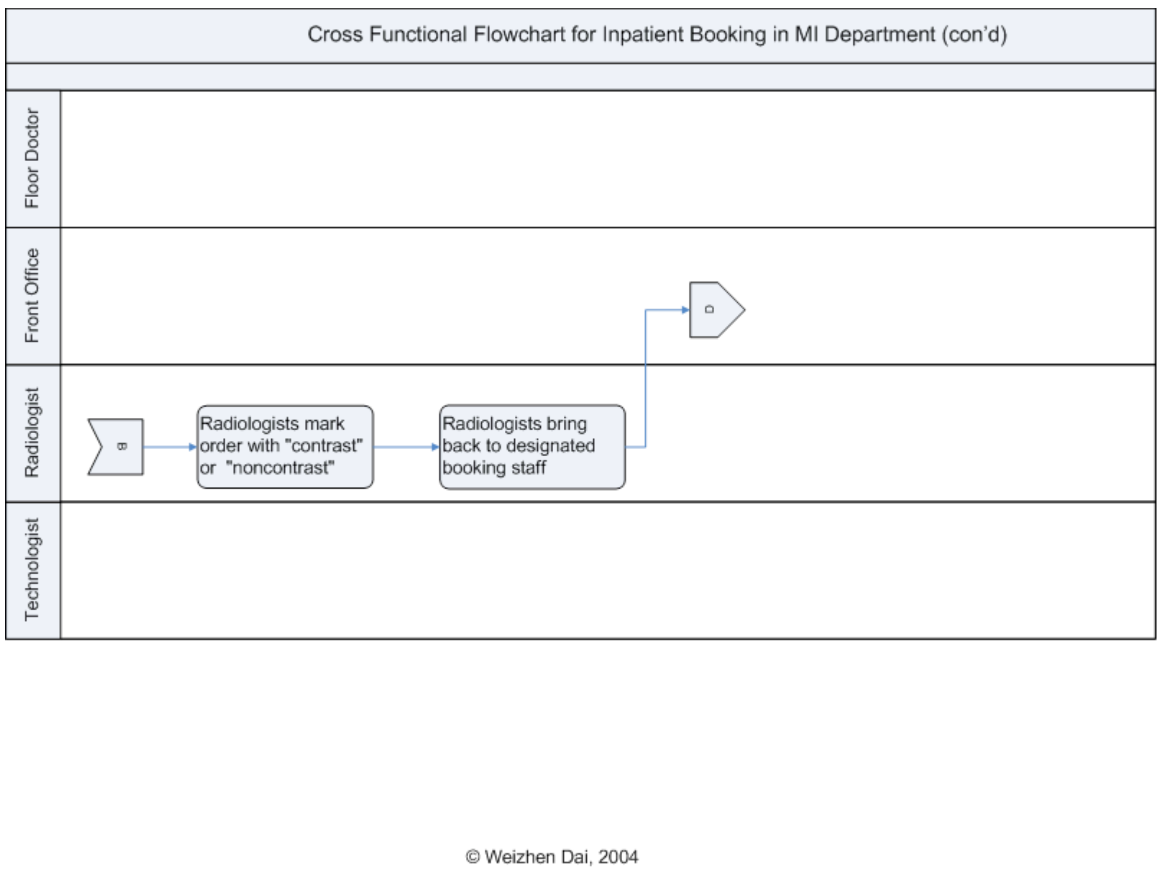

Figure B.3: Workflow: Page 3

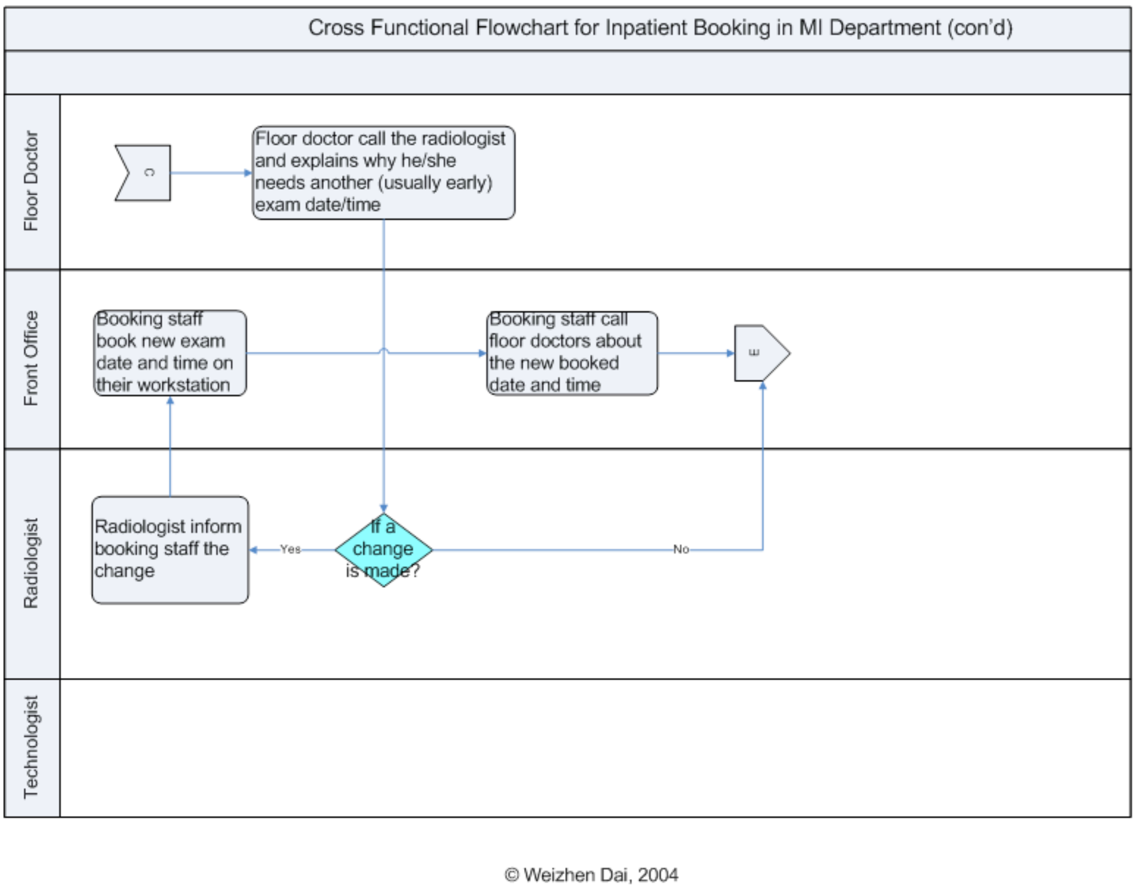

Figure B.4: Workflow: Page 4

Appendix C

The Zoning Concept

C.1 Activity Space

Activity space is analogous to process elements; it is the space zoned for defined activities. The classical definition of workflow made a tacit statement that the boundaries of an activity space cannot be violated. The activity took place in the defined space, and could not overlap with other activities. Using this assumption, there is no information on what effect overlapping processes may have on each other. We maintain the use of this assumption for our current definition.

From our definition, the *work available space* for an activity must be of a size large enough to accommodate its minimum spatial requirements of the workspace element.

C.1.1 The Concept of Buffer Space

The buffer space concept is derived from the circulation space defined in the multiple criteria layout example (Jacobs, 1987). Circulation space is defined as space reserved for movement within the layout adjacent to solid/activity space. Buffer space is based on an activity having an ideal spatial requirement that exceeds the minimum required activity space. An example of this concept is the placement of a pool table in a room. The pool table can be placed in a *work available space* that is equal to the size of a the pool table with a foot of space around the table for player movement based on the minimum spatial requirements of the object. While it would be possible to play a game in that setting, it is far from ideal. The ideal case would be that a buffer would exist around the activity space in which other activities would not occur in order to allow a comfortable experience for the players. The same argument applies in the discussion of workflows. Using our previous description of activity space with one activity per room, the buffer space is the *work available space* outside of the minimum activity space. The walls/*work available space* provide the limit on the available buffer space, and the space can be calculated as the difference between the space in the room, and the minimum activity space of the workflow element.

The impact of the size of the buffer space is varied. If not enough buffer space is available, it will have a negative impact on the ability of the players in completing their game. On the other hand, there are no penalties to the performance of the activity if all activities possessed an infinite buffer space. The penalty would then lie in the transport time required between activities. As the buffer size increases the performance penalty decreases, until large increases in buffer size offer little to no performance benefit.

The penalty associated with violated buffer space is subjective and that has not been formally defined at this time. More research is required to understand the limitation of varying the size of an activity space as well as defining an appropriate buffer space size.

Using this approach, the fitting of activities to existing spaces will take on a new degree of variability. Current approaches treat the sizes of all activities as static objects. Activity space is now a variable entity, and placing an activity in rooms with varying buffers, may have a noticeable effect on the performance of the workflow. For the moment we will utilize the static treatment of activity space under the assumption that a realistic buffer space is built into the definition of its *workspace*.

C.2 Transport Space

Activity space tacitly includes some transport space into its specification via the buffer concept. In order to enter or exit the activity space, some transportation space is required. An example is in a cubicle for a worker: there will be a portion of that space that is used to enter and exit the cubicle, but that space is not used by other coworkers as transport space. We will be applying a definition of transport space, as space that is not also used for activities, but is used to travel to or from an activity space.

The vectors from our *IfcPaths* are still used to describe the path between activity centers, but we are attributing additional properties to the pathway. In most settings, there will be different objects that travel between activity centers. In a hospital this could include patients in wheelchairs, patients in gurneys, and ambulatory individuals traveling at various speeds. The transport space required for each object may vary in terms of both size and speed.

C.2.1 Properties of Transportations Space

Using an amalgamated view for transport space, the route between activity centers becomes a sequence of zones. For a sample workflow, the transportation object travels from start to finish as passes through zones a set of adjacent zones. As it passes through the zones it will affect the use of that zone for all workflows that also pass through that zone.

Unlike activity space, transportation space can be shared with other transport spaces at different temporal instants. The limits on sharing transportation space is equivalent to the bandwidth of the hallway. This concept of transportation space bandwidth is speculative must be treated accordingly. For the purposes of this thesis, the main point of interest is that multiple transportation spaces can be assigned to the same transportation pathway.

C.3 Waiting Space

Waiting space is not defined as activity or transport, and may be separate from undeclared space. The concept of waiting space arises from the simulation concept of queues and the impact they can have on workflows in a space. If we take the example of a waiting room, as the patients wait to travel to the next activity center they will take up space. If system performance is poor, the number of people waiting for service may be significant. If the number of patients waiting exceeds the waiting capacity of the room then the overflow may affect other workflows. As an example, the patients may be forced to wait in adjacent hallways, which would affect the ability of other workflows to pass through the hallway.

This diverges from our original specification of workflows as activity and routes. If we define workflows in terms of activity and transport space then depending on our definition waiting may occur in either space. A queue at a bank demonstrates that the queue may be included as either a part of the activity or the transport space. Waiting occurs in this example due to an interaction between the workflow and the workspace. Choosing to include it as transport would violate our definition of transport space in that it is the unimpeded transport between activity centers. Including it among activity space implies that waiting is a part of the activity and not a consequence of the interaction between the workflow and the space or other elements of the workflow.

C.3.1 Waiting as a component of workflow

Before we proceed, it is important to note the difference between procedural and consequential waiting. Procedural waiting is defined as a part of a process (e.g. catheterization). Consequential waiting is the waiting that occurs due to discontinuities in service availability. We will be treating procedural waiting as an activity due to its relationship to other contextual dimensions. We will be defining waiting space as a sub-set of activity space, similar to buffer space.

C.4 Undeclared/Storage Space

Undeclared space may be separate from waiting space depending on the allocation of activities; it is unlikely that all available space in a facility will be designated for either activity, transportation or waiting. While not tied to a workflow it still has properties that may still provide contextual information for the workflow.

In our specification, activities will be assigned to a room and the space surrounding the activity space within the confines of the room will be treated as buffer space or waiting space. Undeclared space will consist of spaces devoid of activities or route assignments.

Appendix D

Glossary of Terms

AEC Short for Architecture, Engineering and Construction, a domain of research and expertise concerned with the design and construction of facilities.

Arena A simulation application owned by Rockwell Automation.

AFL Automated Facilities Layout. A solution technique originally developed in the 1960's to provide optimal floor plans for facilities.

Classic workflow representation Techniques A collection of representations such as flowcharts, process maps and various forms of graphs. These are representation techniques for static workflows.

Context A term used to represent the collection of contextual dimensions associated with a workflow.

Contextual Dimensions/Contextual Elements The separate entities that collectively define the context of a workflow. The use of dimensions and elements is used interchangeably.

DI Short form for Diagnostic Imaging, a department at Grand River Hospital.

EXPRESS A modeling language used in IFC. It is the data modeling language of STEP.

EXPRESS-G EXPRESS-G is the graphical notation developed within STEP and used for the IFC definition. EXPRESS-G is a subset of the EXPRESS language; all objects drawn in EXPRESS-G can be defined in EXPRESS, but the converse argument is not true.

FM Short form for Facilities Management. The term is used interchangeably to describe applications and processes involved designed for the management of facilities as well as the literature domain with respect to this topic

IAI The International Alliance for Interoperability is a consortium of organizations that collectively seek to improve the productivity and efficiency of the AEC and FM communities. The IAI are the creators of IFC.

IFC The Industry Foundation Classes are a neutral data model created by the IAI. It is based on an object-oriented design based on the use of a building data model. The latest release is version 2.3.

IFCxml The XML specification of the IFC standard. IAI developed an XML specification for use with IFC to improve its interoperability with outside applications.

OR Short form for Operations Research.

Static Workflow Workflows in which the sequence of events remains static over time. Classical workflow representation techniques are based on static workflows.

STEP (ISO 10303) The Standard for the Exchange of Product model data: an ISO standard for the computer-interpretable representation and exchange of industrial product data.

VLSI Very-large-scale integration is the process of combining a large number of transistor based circuits onto a single chip to form an integrated circuit.

Workflow A representation of a repeatable sequence of events that can be documented and learned. It is enabled by the organization of resources and defined entities.

Workspace A concept developed in this thesis to describe the projection of a workflow on 3-space. The workspace of a workflow contains only 3-dimensional entities and is dimensionally equivalent to the work available space.

Work Available Space A concept developed in this thesis to describe the projection of a facility on 3-space. The work available space of a facility contains only 3-dimensional entities and is dimensionally equivalent to the workspace. It is the free space in a facility that is used by workflow.

XML A general purpose markup language known as the Extensible Markup Language. XML allows users to define their own tags in order to facilitate the sharing of data across multiple information systems.

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