# Computer Aided DfC (Design for Construction) in the Building and Construction Industries

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## Abstract

Although the integration of design and construction (also called Design for Construction, DfC) has always been an important issue in the building industries, it is still not realised satisfactorily. Problems that occur in the construction phase, usually have to do with communication between different processes. Especially the transfer of construction knowledge to the design process causes problems. With new IT technologies DfC is within reach. This paper describes how new IT technologies can help to reach Computer Aided DfC. ISO standardisation developments form the basis for CADfC. Especially the product modelling approach of STEP (STandard for the Exchange of Product model data) is interesting. However, modeling of product data is not enough. That is why we developed an extended version for all project information.

## Introduction

In the Building and Construction Industries, Design for Construction (DfC) has always been an important design aspect. It has always been important to ensure the realisation of a designed building, within time and costs limits. However, the construction process is not the only aspect the designer of a building has to take into account: the government demands the building to conform to security, environmental and constructive regulations, the client requires low costs and high functionality and finally the architect is interested in appearance of the building and its fitting into the environment. All those other considerations and problems with communication made that DfC was shifted somewhat to the background. Now, with current IT technologies in mind, it is possible to do something on DfC again.

DfC covers the integration of the design, planning and construction processes. The main problem is the communication between these processes. This problem has organisational and technical backgrounds. Reuse of construction knowledge is difficult because designers are often not confronted with consequences of design failures. The time gap between designing and using a building is too large. Designers are also often not really (financially) concerned with the construction process, because it is performed by other companies. The last decades more and more knowledge, computer systems and technologies had to be integrated. However, most communication is still paper work, which is time consuming and open to inconsistencies and misinterpretations. Simple, redundant 2D drawings can not fulfil the new integration demands. Because of the problems with the transfer of construction knowledge to the designers it is impossible to have clear insight in the constructability of the building during the design process. Designers can only rely on their experience. This means that they tend to use 'old' building methods that have proven their

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value in practice, and that they are not open to new methods.

The goal of DfC is first to overcome the technical communication problems. With technical possibilities of exchange of information and knowledge between building processes the way is open for an organisational change. This may lead to the improvement of:

1 the profitability of the construction process,
2 the productivity of the resources,
3 the quality of the product and
4 the working environment for construction workers.

In 1989 Delft University of Technology started a Computer Integrated Construction (CIC) project, in which the results of several graduation projects are combined. One of the projects is called 'Computer Aided DfC for the Building and Construction Industries'. This project investigates how computers can help to realise DfC. Partners of the project are Delft University of Technology, TNO Building and Construction Research and the main contractor Ballast Nedam. This paper deals with some of the results reached so far.

The paper starts with a survey of the goals we want to reach with (Computer Aided) DfC: the next chapter describes what DfC related information and knowledge is transferred between design, planning and construction and the following chapter describes how we can get insight in the constructability of a designed building. A chapter on IT Developments deals with the new tools that are available for the realisation of DfC: the latest IT developments. In the following chapter these new IT technologies are applied for Computer Aided DfC (CADfC). It becomes clear that CADfC can only be reached with a standard for the exchange of project information. The main properties of such a standard are worked out in the chapter on Project Information Exchange Standard. The Building Project Model, described concisely in the following chapter, can be such an exchange standard. Finally some conclusions are drawn in the final chapter.

## DfC related Communication

The main problem to be solved with DfC is the communication between design, planning and construction. To investigate what information and knowledge is transferred between those processes, we executed an information analyses for the realisation of prefab concrete structures.

The realisation of a prefab concrete structure is a complex process. We used the graphical process analyses method IDEF-0 [1] to model the whole realisation process. From this total process model the main DfC related processes with their information flows are extracted. This means that not DfC related processes are not considered here, e.g. acquisition, tendering, legal contracts between partners, administration, conformance checking by the government, project managing, etc. In figure 1 the main DfC related processes are shown: 'design structure', 'plan construction' and 'construct structure'.

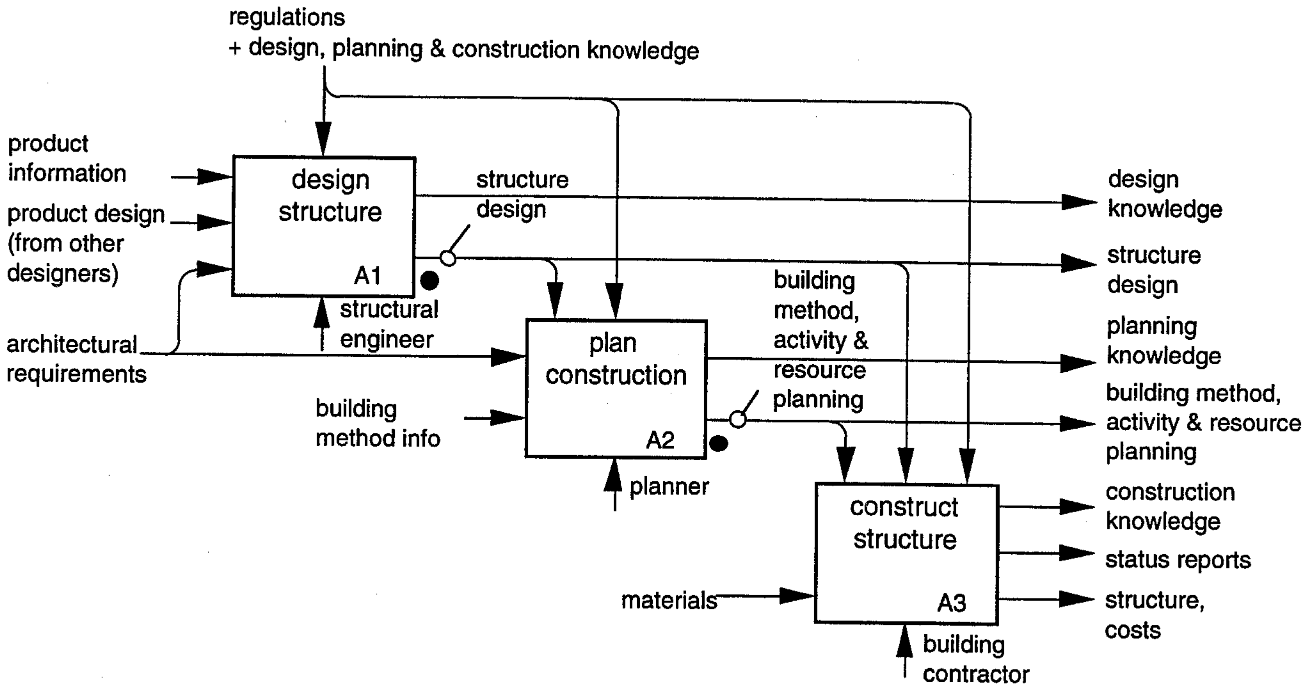


Figure 1 IDEF-0 diagram of the realisation processes of a prefab concrete structure

The structural engineer designs a concrete structure in detail that fits within the product dependant architectural requirements and the requirements of other designers, like the HVAC expert. Standardised solutions (the product information) and project dependent planning information are used as input to make a design. The design must conform to (governmental) regulations and knowledge rules. The knowledge mainly concerns constructive knowledge. The engineer is supported by CAE and CAD (Computer Aided Engineering and Computer Aided Design or Drafting) systems. Then the planner makes the construction plannings. The design and information on standardised building methods is used as input to determine the building method, the activity planning and the resource planning. These plannings have to fit in the requirements with regard to time, costs and use of generally available resources. They also have to conform to regulations and knowledge. Knowledge concerns process planning and logistics. The planning process is supported by CAPP and CAL (Computer Aided Process Planning and Computer Aided Logistics) systems. The last main process is the construction process itself. This process consists of three parts: first the elements are prefabricated in the factory, then they are transported to the building site and finally the elements are assembled to a structure. If necessary the element are stored near the factory or on the building site. The construction processes must conform to the plannings and the design and of course to regulations and construction knowledge. Some construction processes are supported by CAM (Computer Aided Manufacturing) systems, like numerical controlled machines or even robots.

In this (simplified) process diagram the DfC related communication concerns project dependant information and project independent knowledge. These aspects can be transferred forward (e.g. from design to process planning) or backward (e.g. from construction to design). The following DfC related flows can be distinguished:

- forward information exchange from design via planning to construction (this is the main information flow in a production process);

- backward exchange of construction knowledge to planning and design, and exchange of planning knowledge to design (e.g. knowledge about construction costs and duration);
- backward exchange of planning and construction information (e.g. information from planning to design about the availability of resources);
- backward feedback on design or planning decisions, (e.g. from planning to design: the structure you designed can not be assembled with the available resources or within the given time limits).

Next to these information and knowledge flows another aspect of communication is important for DfC: the forward shift of responsibility. This means that the designer does not work out the design in all details. For some details he only determines the requirements and leaves the final choice to other designers or to the producer. In our example the architect does not work out the design of the concrete structure in all details: he only gives requirements and gross dimensions. The constructive designer determines the divisions in elements and the detailed dimensions, both according to the chosen construction method and the available resources.

The DfC information and knowledge flows complement each other. The designer tries to take the availability of resources into consideration as good as possible; however, the planner always checks the design and gives feedback if necessary. The designer has to make a choice between taking construction knowledge into account or shifting the responsibility for design decisions to the planner. In the last case the planner must have some design knowledge.

## How to ensure constructability

As a consequence of the communication problems another problem occurs: there are no techniques to get insight in the constructability of a building during design. Because of the lack of such techniques in the Building Industries, the normal procedure is to use experience and common sense during design. In well organised projects the design is passed to the planner for comment on different design phases, but often the planner has little or no influence on the design at all. In those cases it is necessary to have techniques to check a design against construction demands and to have construction rules to be regarded during design.

In the Mechanical Industries they are already working on those techniques and rules. Important developments are Design for Assembly (DfA) (or Design for Manufacturing (DfM)) and Flexible Production Automation (FPA). The following describes some of these developments and what the Building Industries can learn from the Mechanical Industries despite of the differences.

### DfA and FPA developments in the Mechanical Industries

In the field of DfA Boothroyd and Dewhurst [Boothroyd 87] developed a quantitative assemblability evaluation method, based on an empirical study of costs associated with manual, robotic and automated assembly processes. They suggest that the best way to reduce costs is to reduce the number of components that must be assembled. They say that it is only necessary to introduce a new element if there is a gross movement of that element relative to other elements, or if it is necessary to use different material or if there are purposes of service and maintenance. After consideration of these criteria for part-count reduction a worksheet is used to determine the assemblability in terms of costs. This worksheet forms the basis for comparison with other alternatives.

Another method for the evaluation of the assemblability is developed by Hitachi [Miyawaka 86]. This so-called Assemblability Evaluation Method (AEM) helps to identify the weak points of a design. The method prescribes a way to calculate the values of evaluation indices, that can be compared with target values. If this is deemed necessary, the design can be improved. The method gives indications where to find unfavourable parts or subassemblies in the design. In this way AEM gives arguments for new designs, that would not be accepted normally.

In the field of DfA and FPA Andreasen et al [Andreasen 88][Andreasen 87] work on design rules for ease of assembly and flexibility in the Mechanical Industries. They describe rules for identification, orientation, transportation, storage, composing (insertion, joining method) and quality checking of assemblies. They state that DfA and FPA asks for higher quality and more quality control, (flexible) mechanisation and automation, design for standard equipment, avoidance of variants, uniform variants and a good working environment. The product structure and the components should be designed for ease of assembly.

### DfA and FPA applied to the Building Industries

Building Industries can take advantage of the experience with DfA and FPA of the Mechanical Industries. However, DfA and FPA can not be copied to the Building Industries without adaptations, because there are too many differences. These differences should be recognised first.

Many of the differences originate from historical backgrounds. First of all the organisational structures differ very much: in the Building Industries every project has different partners, there is much competition between the partners (no co-makership), design and production are separated and the organisations are project oriented. This means e.g. that it is often only possible to sub-optimise with regard to construction aspects. Because of the high competition between building partners, the profit margins are low and usually clients profit from costs reductions. Also the legal structure complicates the introduction of things like DfC. For example in the Netherlands the HVAC advisor gets a percentage of the installation costs, so he is by definition not interested in costs reduction. In the Building Industries products are often one of a kind, so there is relative less money and time for design optimisations. Last but not least the working conditions in the Building Industries are often bad and unpredictable.

The DfA and FPA rules should be adapted to the Building Industries and a constructability evaluation methodology should be developed. Because the Building Industries are less structured, less automated and have a more complex organisation structure, it is difficult to identify the design rules and to qualify and quantify the constructability of a design. It is only possible to do this with the help of computers in which construction knowledge is formalised. The new IT developments that will be introduced in the next chapter will make this possible.

## IT developments

The most important IT developments DfC can profit from to solve the communication problems are: professional personal workstations, telematics, Computer Integrated Construction, knowledge technology and mechatronics and robotics.

The growing infiltration of professional personal workstations and the new possibilities of telematics are of great importance for the Building Industries in general. These developments are a good starting point for the realisation of DfC, but they are not of special interest for this paper. Developments in telematics that are more specific for DfC are EDI/PDI (Electronic Data Interchange and Product Data Interchange), MAP/TOP (Manufacturing Automation Protocol and Technical and Office Protocol) [Jones 88], STEP (STandard for the Exchange of Product data), and MMS (Manufacturing Message Specification) [ISO/DIS 9506 88]. EDI and PDI focus on the standardisation of data exchange formats. EDI concentrates on commercial trade data and PDI on technical product data. ISO (the International Organisation for Standardisation) is developing a standard for communication between computer applications. This standard fits in the 7 layered OSI (Open Systems Interconnection) framework. For an office environment TOP is developed, for industrial environment MAP. STEP is an example of PDI and is built on top of MAP/TOP. MMS standardises a protocol for the communication with numerical controlled machines and robots and fits in the seventh layer of MAP.

CIC (Computer Integrated Construction) aims at the integration of islands of automation, like CAD, CAE, CAPP, CAL and CAM. The basis for the integration of those CIC-components is the integration of the information they use and/or produce. This information is integrated with standards for data exchange on different levels of abstraction. These standards fit in the OSI framework. Standards like TOP, MAP, STEP and MMS are tools for the integration of CIC components.

An IT development on another level is knowledge engineering. Knowledge engineering leads to local Expert Systems, in which knowledge of a specific knowledge domain is represented in rules. These rules can be interpreted by computers. Expert Systems can be used to support the decision making process.

The introduction of mechatronics and robotics in the Building Industries lacks behind to the introduction in the Mechanical and Electronics Industries. The reason for this lack behind is the special character of the building industry: the products are mostly 'one of a kind', the products are very large and the production is located at sites instead of factories. The currently commercially available robot systems can not cope with such a unstructured environment. Next to this hardware shortcomings there are software shortcomings. Robots in a building environment require a high level, flexible method of programming. The solution of this communication problem comes within reach with the application of IT developments like STEP and MMS [Krom 91].

## Computer Aided DfC

With the currently available IT tools, as mentioned in the respective chapter, most of the problems of DfC, as mentioned earlier, can be solved. Product models based on STEP can be used for the communication of data between computer application. For the transfer of data from design and planning systems to numerical controlled machines MMS can be used. Also the exchange of data between planning and construction workers can be structured with STEP based product models. This requires workstations to be available on the building site. The communication between partners can be supported by EDI and PDI.

For the exchange of construction knowledge to the design process also the STEP product modeling approach can be used. De Waard showed something similar in his thesis 'Computer Aided Conformance Checking' [Waard 92a][Waard 92b]. He shows how residential building designs are checked against building regulations. The design is modeled in a product model based on STEP, the regulations are modeled in a regulations view product model and in rules. In the same way we can check if a design, modeled in a project model, conforms to a construction view project model and to construction rules. Construction rules can be compared with the DfA rules applied in the Mechanical

Industries.

Construction knowledge can also be implemented in local Expert Systems that help to evaluate the constructability of a design and to improve it if necessary. The problem with this kind of local Expert Systems is that they only take one aspect of a total design into consideration. A DfC Expert System only takes the constructability into consideration. As mentioned in the introduction a designer has also to consider governmental regulations, (non constructive) costs, functionality, architectural requirements etc. Therefore this local expert system has to be integrated with other knowledge representations. T his integration can be realised with STEP based product models.

Summarised can be said that the ISO developments, and especially the STEP developments, form the basis for the solution of the DfC related problems. However, STEP only considers the exchange of product information, where DfC also requires the exchange of process and resource information. Therefore, the solution of the DfC related problems asks for a standard for the exchange of all project information, bases on STEP (and thereby on the other ISO developments).

## Project Information Exchange Standard

As seen in the foregoing DfC requires an international accepted standard for the exchange of project information. Project information means project properties (or data) as well as project behaviour (or procedures). It seems to be interesting to extend the STEP *product* modeling approach to a *project* modelling approach. The first thing to do is to add activity and resource information to the product model. The main entities of such a project model, Product, Activity and Resource, are respectively related to shape and material, to time and to costs. We reported already in [Luiten 89] and more recently in [Luiten 91] on this subject. Also the Finish RATAS project [Karstila 91] and the ESPRIT project IMPPACT [Gielingh 92] study this subject. This chapter deals with the relation between the three entities.

For the relation between Product, Activity and Resource we have to introduce the new entities Result and Actor (see NIAM [Nijssen 89] diagram of figure 2). An Actor transforms an old Result in a new Result. This transformation is called an Activity. For DfC we look at construction activities, which means that the new Result normally is a new state of the Product. The starting point of an Activity is the Result of another Activity. An Activity is supported by Resources.

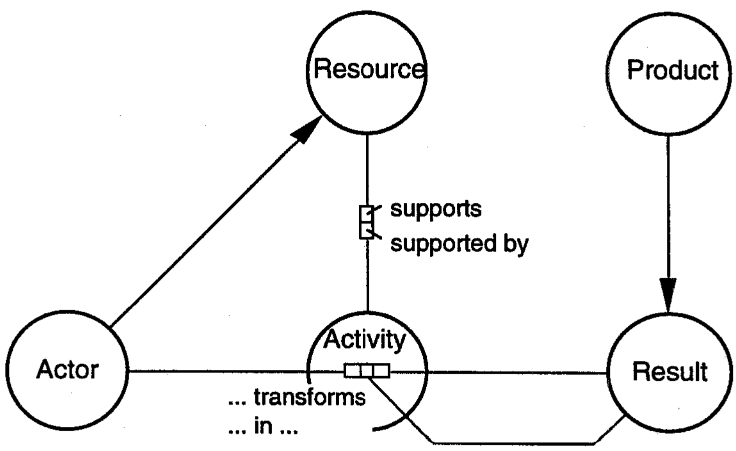


Figure 2 Introduction of Actor and Result to relate Product, Activity and Resource

The introduction of Actor introduces a new aspect to the project model: *actor views*. We consider information and knowledge on one building and one building project, but there are numerous actors. Each actor has his own actor view on the building. Figures 3 and 4 show the view of an architect and the view of a construction planner on an office building. The two actors, looking from a different viewpoint to the same building, concentrate on different aspects. The architect mainly concentrates on the functional spaces of the building when it is used. Other systems in the building, like the bearing structure and the HVAC systems, help to realise the requirements of the functional spaces. The construction planner is mainly interested in the construction phase of the structure. He sees the building as a set of components that must be assembled by construction workers with equipment on the building site.

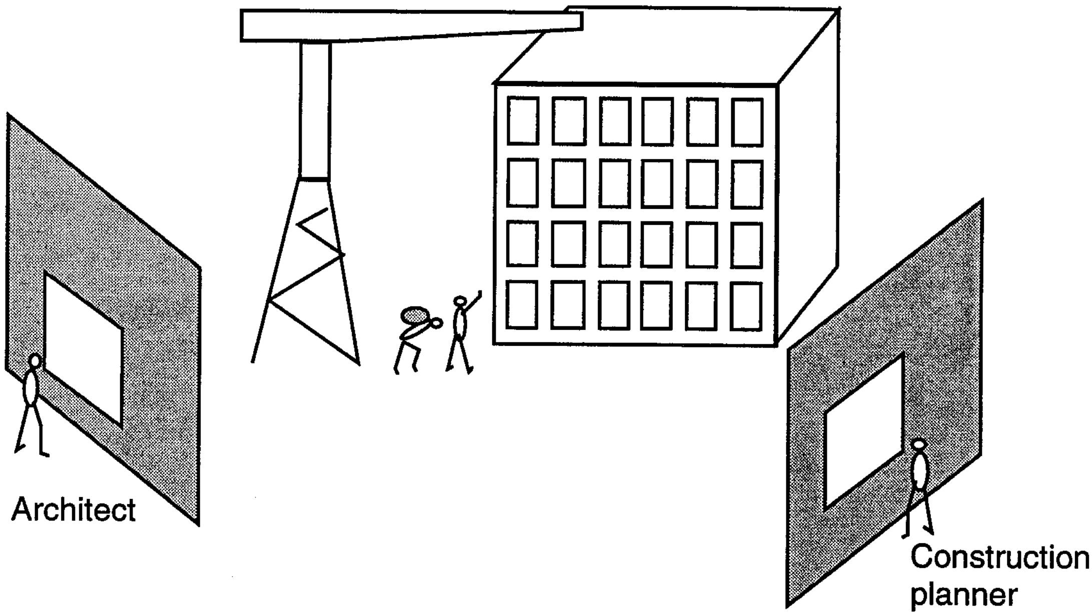


Figure 3 Different views on a building: architect and construction planner look at a building through different windows

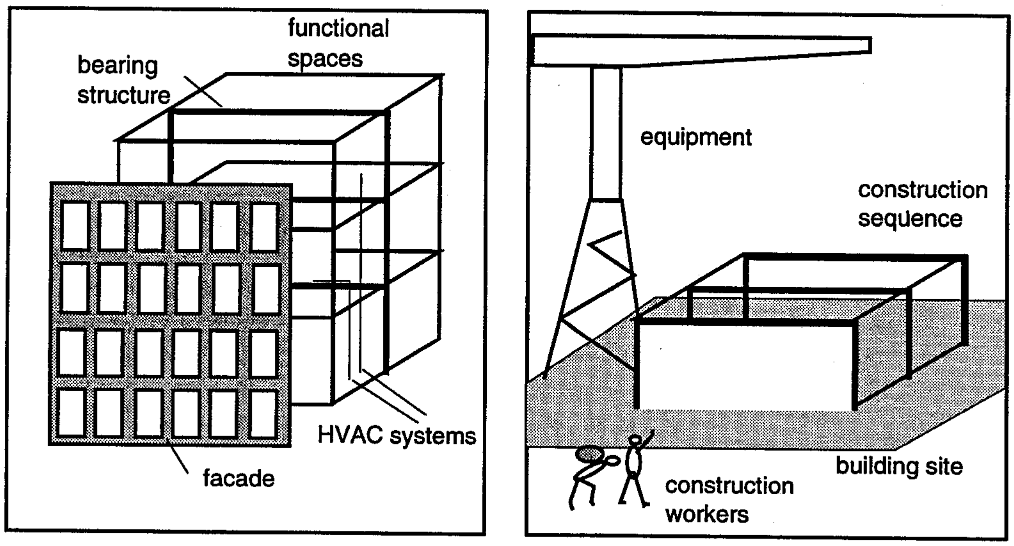


Figure 4 Architect view and construction planner view on the same building

The project model helps to integrate the different views. The project model is a central, neutral model, where all actor views can be deducted from (see figure 5). Communication between actors goes from an actor view model via the neutral project model to the other actor view model. The conversion between the project model and the view models must be standardised. The computer applications of the actors work on the information modeled in the view models.

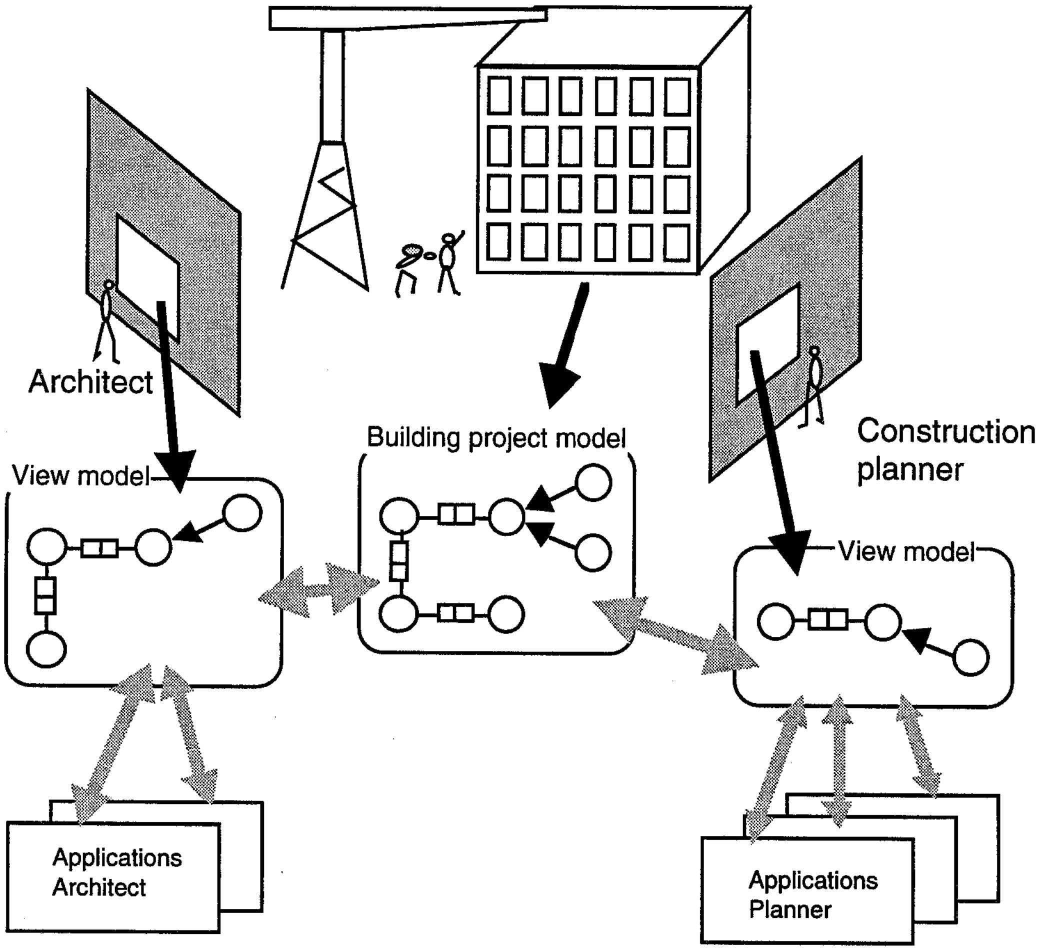


Figure 5 Conversions between project model and view models are standardised. Application programs work on actor view models.

The introduction of Actor and Result makes it also possible to use project models for project management. A project manager co-ordinates the activities of the different actors from initiative, via design and planning to construction. For this project co-ordination a new relation must be introduced: an actor orders another actor to perform an activity. The order is legally put down in a contract, that describes the starting and ending situation and the conditions of an activity.

## Building Project Model

CADfC aims to solve the communication problem between actors. This problem is now 'reduced' to developing a project model that stores all project information and integrates the different actor views. We call such a model a Building Project Model (BPM). This chapter only describes the main characteristics of the BPM. For more details we refer to [Luiten 89] and [Luiten 91].

In the BPM we try to model the reality of a building project. Facts of reality can be arranged in abstraction levels. The abstraction levels have a hierarchy, formed by the relations between the levels. For every type of relation there is an abstraction mechanism. Four abstraction mechanisms form the basis for the other mechanisms: intension / extension, generalisation / specialisation, aggregation / decomposition and views.

The first abstraction mechanism, intension / extension, uses the relation 'is described by'. For example: the reality of a building project is described by a project model, which is described by a project type model, which is described by a NIAM diagram.

The second abstraction mechanism, generalisation / specialisation, uses the relation 'is a special case of'. Let's look, e.g. at a product type model: a high rise office building is a special case of an office building, which is a special case of a building, which is a special case of a building product. This mechanism uses the fact that different objects have properties and behaviour in common. On the highest generalisation level, properties and behaviour are modeled which are applicable to all objects in building projects. On specific levels, properties and behaviour are specialised for subsets of objects. This means that general properties and behaviour are restricted and that new properties and behaviour are added.

The third abstraction mechanism, aggregation / decomposition, uses the relation 'is part of'. For example a reinforcement bar is part of reinforcement cage, which is part of a prefab concrete element, which is part of a concrete structure.

The fourth abstraction mechanism, views, uses the relation 'can be deducted from'. We have seen this mechanism in the chapter on Project Information Exchange Standard: data for an application program can be deducted from an actor view model, which can be deducted from project model.

These four basis abstraction mechanisms are being worked out theoretically. For the theoretical basis we use already well accepted paradigms from logic and mathematics, like typed set theory, predicate calculus and abstract data types with algebraic specification. With this theoretical basis a framework for the BPM has been formed.

At the same time we are working on an prototype project modeling environment, PMshell, for the implementation of the BPM. PMshell is written in the computer language Eiffel. Eiffel is based on the Object Oriented paradigm, as described in [Meyer 88]. PMshell helps to bridge the gap between specification, implementation and documentation. It supports programming users as well as modeling users. Programming users specify and implement project type models, that are used by modelling users to model specific projects. Project type models can be structured into specification layers. PMshell has interfaces with a database system, with EXPRESS files and STEP physical files. EXPRESS is the information modelling standard of STEP, STEP physical file format is the data exchange standard of STEP. PMshell has a graphical, interactive user interface. For more information on PMshell see [Luiten 92].

With PMshell we are able to implement the BPM and apply the system for prefab concrete structures realised by a prefab element supplier. This implementation will be used in practice to test our ideas on Computer Aided Design for Construction. We will report on that later.

## Conclusions

The realisation of Computer Aided DfC (Design for Construction) depends on the development and acceptation of an international standard for the exchange of project information. The best way to develop such a standard seems to extend the ISO/STEP product modeling approach to project modeling. The acceptation of the standard is more a political than a technical problem: introduction of the standard will change organisational structures in the Building Industries drastically. It means that partners, who often compete each other in the current situation, must work together and share information, knowledge and responsibility in the new situation. This will only be accepted if the technical improvement is proven in practice more then satisfactorily. This means that the introduction of the standard must take place step by step, and that each step must have direct positive consequences for all partners involved.

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