Computer Aided Dimensional Control in Building Construction

PROEFSCHRIFT

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door

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geboren te Shanxi, China
To the memory of my dear mother,

to my father

and Dianwen
Preface

The Building-Construction industry is facing increased demands from society, i.e. higher quality, shorter lead times, more customisation, more care for the environment, better working conditions, less disturbance for the surrounding, and more.

Improving the quality of the construction process is one of the responses to society’s demands that the Building-Construction can make, which is worthwhile looking into. Many problems relate to measurement and dimensional control errors. Tolerances can’t be met; components do not fit; and cheaper work-methods can’t be applied. All are waste and produce cost of failure, delay, and agony, often even leading to legal hassling where nobody can win.

This thesis focuses on the improvement of dimensional control and possible ICT usage to contribute to solving the problems.

The research has been carried out at Eindhoven University of Technology (TUE) in the Netherlands where the Department of Construction Engineering and Management (UT) is working on dimensional control for many years, providing me with a large body of dimensional control knowledge that sips through in almost every page and paragraph.

This research has been sponsored by TUE, TNO Bouw, and SBR (Stichting BouwResearch). I am very grateful to these organizations. Also this research and thesis cannot and should not be credited to me alone. I could not have achieved without the help of others. First of all I would like to thank my supervisor Ger Maas for his guidance and enthusiasm. It was a pity that halfway my study Ger mostly left TUE to stay only for one day a week. I also want to thank Frits Tolman from Delft University of Technology (TUD) who has supported the ICT-part of my work. My thanks also go to Arjen Broens for his support on construction surveying and help with arranging my case study on the construction site in Apeldoorn. I also like to thank Peter van der Veer from TUD and Henk van
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INTRODUCTION

This chapter introduces the research problem, describes the initial research objectives, scope and methodology, and gives an overview of the structure of the thesis.

1.1 INTRODUCTION TO THE RESEARCH

Dimensional control in the building industry can be defined as the operational techniques and activities that are necessary for the assurance of the defined dimensional quality of a building (Hoof, 1986). The purpose of dimensional control is to minimize the negative effects of deviations on: the functioning of the building, and on cost and labour. To ensure adequate dimensional control, building components and formworks must be set out and assembled in correct positions, with an overall accuracy that meets the requirements.

The increased use of prefabricated components, the complexity of new building shapes, and the speeding up of production in construction, demand an efficient and precise dimensional control. Meanwhile Information and Communication Technology (ICT) increasingly supports construction. Besides Computer Aided
Drawing and Design, Cost Estimation, Project Management, Planning and Scheduling, advanced electronic instruments, such as Total Stations, are being used to support setting out and positioning of building components on construction sites.

In order to achieve precise and efficient dimensional control, a dimensional control plan must be designed before the building is constructed. The plan includes: (1) a tolerance plan, (2) an assembling plan, (3) a setting out plan and (4) a dimension-monitoring plan.

Presently the contractor and engineers often make the dimension control plan based on drawings and specifications delivered by the architect. The drawings are often in CAD format, mostly AutoCAD drawings. The dimensional control plan constitutes, to a great extent, information on points for different aspects of dimensional control, which can then be transferred into a Total Station. Designing such a plan is a complex issue requiring detailed information and a lot of experience. Planners must interpret the CAD drawings, make an inventory of points needed, select appropriate points for different purposes and often add them to the drawings. Every project is different and not every planner is experienced, consequently the quality of the plan varies from project to project, and also from designer to designer.

Although, as described above, CAD systems and Total Stations have been used for the purpose of dimensional control, the link between them is missing, which often makes digital points information hard to find.

To improve the dimensional control of on-site construction projects, this research (1) tries to capture the knowledge required to design an adequate dimensional control plan and make that knowledge more generally available and (2) build a digital connection between CAD systems and Total Stations. And the research is focused on prefabricated concrete building structural elements.
The initial research questions are formulated as follows:

- Is it possible to develop an ‘intelligent’ instrument that supports the less experienced planners to develop adequate dimensional control plans?

- How to facilitate the digital information flow between CAD systems and Total Stations?

1.2 STRUCTURE OF THE THESIS

The structure of the thesis is described in the following paragraphs:

Chapter 2 gives a detailed description of the subject of dimensional control in building construction with the focus on setting out and positioning prefabricated structural elements. The setting out process and positioning process including the use of Total Station and other often used equipment are described in detail; the concept of main control points, references, setting out points, positioning points, product measure, setting out measure and positioning measure is introduced; the process of designing the plan of dimensional control is discussed and finally the research problem is pointed out.

Chapter 3 analyses the current situation of dimensional control in building construction with the focus on the Netherlands. It describes the Dutch standards for measures and measuring in construction NEN series 14. It also depicts a picture of the fragmentation of the building design and construction process. It also investigates the dimensional control situation of prefabricated structural elements on building sites by conducting surveys on 21 sites in the Netherlands. Finally the conclusion on dimensional control is drawn.

Chapter 4 analyses the state-of-art of Information and Communication Technology (ICT) relevant for dimensional control in building construction, including the development of CAD systems, Product Data Technology, Knowledge Technology, Virtual Reality, and programming languages and environments.
Chapter 5 reformulates the research questions based on the analyses of the previous chapters.

Chapter 6 analyses the research problem, proposes a solution for simulating the dimensional deviations including representation of engineering experience knowledge, and presents the underlying information model defined in UML (Unified Modelling Language).

Chapter 7 proposes a computer-aided system for dimensional control based on the model presented in Chapter 6. It defines the system requirement, presents the system’s functional design and gives some details on the prototype implementation.

Chapter 8 evaluates the model and computer aided system by studying the results of a case study performed in Apeldoorn, Netherlands.

Chapter 9 presents the conclusions of this whole Ph.D. study and recommends some further work for the future.
DIMENSIONAL CONTROL IN BUILDING CONSTRUCTION

This chapter gives a detailed description of the subject of dimensional control in Building Construction with the focus on setting out and positioning prefabricated structural elements. Also the research problem is indicated.

2.1 INTRODUCTION

After briefly explaining of the role of dimensional control in building design and construction, an introduction is given to the building construction process of direct importance to ensure dimensional quality. The principle of the Total Station and its latest development including communicating with a computer is explained; the setting out process and positioning process including the use of Total Stations and other often used equipment is described in detail; the concept of main control points, references, setting out points, positioning points, product measure, setting out measure and positioning measure is introduced. Then the process of designing the plan of dimensional control is discussed and finally the research problem is pointed out.
2.2 BUILDING DESIGN AND CONSTRUCTION

Dimensional control in the building industry can be defined as the operational techniques and activities that are necessary for the assurance of the predefined dimension quality of a building (Hoof, 1986). The purpose of dimensional control is to minimize negative influence of too big deviations with respect to functioning of the building, cost and labour circumstances. To achieve this purpose, three groups of people participate in construction process and they must coordinate with one another. They are designers of the building, designers of the construction plan and constructor of the building. Figure 2.1 shows the role of dimensional control in building design and construction. It also gives an overview of three groups of participants, as mentioned above, and their work related to dimensional control.

As shown in Figure 2.1, with requirements reasonably defined, the architect begins designing the building with the help of the structure engineer. They complete the design in documented form - in a combination of the building drawings and plans. The design is then transferred to the construction site, where it is translated into practical dimensions. Throughout this process, various plans and tolerances are considered to ensure the accuracy and functionality of the building.
written specifications. The drawings assure proper form and dimensions, and specifications control the quality of the construction. With regard to dimensional control, ideal dimensions of building components are given in the drawing, and dimension tolerances are specified in the specifications.

Before the building is constructed, the contractor and engineers must deliver a construction plan and work drawings. Generally, a construction plan consists of a transport plan, a site plan, a dimensional control plan, a time and cost plan, a logistics plan, and a safety and health plan. In a dimensional control plan, the tolerance plan, assembling plan, setting out plan, and dimension monitoring plan are indispensable. In work drawings, building details with their dimensions are shown. After the dimensional control plan is worked out, the predicted dimension quality is known and additional information is put in the work drawings.

Finally, constructors produce building components and even the whole building with practical dimensions using material and equipment on site.

2.3 BUILDING CONSTRUCTION PROCESSES

This section gives a description of building construction processes, focusing on the construction of building structures in non-traditional ways, either prefabricated building components, or in-situ casting of concrete. As shown in Figure 2.2, four kinds of construction processes can be distinguished, and they have relationship with one another. These four are prefabricating, setting out, assembling and in-situ casting. Although Figure 2.2 shows especially the processing of concrete as building material, it also holds true for the construction made of other materials.

With respect to concrete precasting, a mould is manufactured in the factory, and then concrete is poured in. After hardening, prefabricated products are transported to and assembled on construction site. That is to say, the products can be brought to a certain position, assembled with one another, and then fastened. In addition to prefabricating, one can also construct a formwork by assembling its separate parts. To ensure precise dimensional control, building components or formworks must be set out in a correct position, and then must be assembled, with an overall
accuracy that meets the requirements set to them. The dimensional accuracy should be checked during the construction process.

Setting out has close relation with land surveying. The field of land surveying, which, put in its simplest form, is the science and art of measuring, recording and drawing to scale, the size and shape of the natural and man-made features on the surface of the earth (Irvine, 1995). The objective of land surveying is to produce a scaled plan of an area. The process of setting out involves locating precisely the position of a building using the information provided by the architect's or engineer's drawing. The basic equipment used in traditional surveying and setting out is: the tape for measuring lengths, the level for measuring height differences
and the theodolite for measuring angles (Bell, 1993). With the rapid development of electronic instruments, EDM (electromagnetic distance measurement) and Total Stations have also been introduced into the field of land surveying and setting out process. Total Stations are one of the most advanced electronic surveying instruments.

In the following sections, the subject of Total Stations, setting out and assembling has been given more detailed description, which includes the definitions, processes and equipment used during the process.

2.3.1 Total Stations

A Total Station is the combination of a traditional theodolite (optical angle measurement device) and a laser distance measurement sensor. It measures the
location of a reflecting prism and gives spherical coordinates. It can be best
described as very accurate, distance-measuring electronic theodolites capable of
diverse mapping and position-measuring tasks. Figure 2.3 shows a Total Station.

Total Stations combine a number of technologies. Concerning angle and distance
measuring, they have remarkable accuracy. As an extension of traditional transits
and theodolites, they have an ability to register very fine angular divisions; they
measure the distance to the target point with an infrared laser emitted by the EDM
(electronic distance measuring device) and reflected by a prism held vertically
above or below the actual point of interest. The actual accuracy is determined by
the wavelength of the light used.

Total Stations have one or two LCD (liquid crystal) displays, and some are
capable of simple graphical display. Apart from producing the same basic
spherical measures as optical survey instruments, Total Stations take additional
data and then calculate additional measures; most importantly, they most are
capable of simultaneous trigonometric conversion of spherical survey coordinates
into Cartesian orthogonal measures--usually east, north, and altitude. Beyond these
simple transformations, and most Total Stations carry a number of useful
programs in their memory. Another function is useful for setting out and
positioning building components. The coordinates of desired points can be input
manually or from data registers, and then the instrument will direct the user to the
points. The screen will indicate the horizontal and vertical alignments of the point
to be found, and then will report how far the prism target and must be displaced
out or in along the radial line of alignment. The diversity and capability of
available programs is increasing through new input and linkage devices that permit
the use of complex code. The standardization of PCMCIA-type cards and the
inclusion of such slots on the Total Stations now allow personal computer
programs to be easily transferred to the instrument.

To be effective, the data the Total Station gathers and transforms must be input
into a computer, and vice versa. These upload and download transfers can be done
directly or through an intermediary storage device. One can use a memory card or
fieldbook as an intermediary device, as shown in Figure 2.4.
With the development of Total Stations, in addition to ever-increasing accuracy, there are some very useful features emerging. Most outstanding are the motorized and automatic target recognition instruments starting to appear on the market. Automatic target recognition helps in setting out and positioning building components. Normally, two persons need to work together when using a Total Station. One of the most time-consuming tasks is bringing the rod person into line with the theodolite's orientation. The new feature makes one-person operation possible, because the Total Station will track the reflector and its functions can be radio-controlled by the person holding the reflector.
2.3.2 Setting out

Every building or engineering structure that is constructed must undergo a setting out procedure to ensure that it is the correct size, in the correct plan position and at the correct level. In general terms, setting out consists of transferring detail from a drawing to a piece of ground. On the drawing details are given of nearby existing buildings and features and the proposed work to be set out. It is possible to extract from the existing detail lines of reference to which new work can be referred such as building lines, base lines and grid lines.

Setting out on building sites is a combination of measuring and marking. The marks, as the result of setting out, can be pencil lines, nails, scratches and so forth. Setting out has two purposes. The first purpose is to define intended positions of building(s) horizontally and vertically on the accessible building construction terrain. That is to say, one needs to set out the building(s) and to establish a point of known level on the site which can be used to determine floor and drain invert levels. The second purpose is to define positions of individual building components and temporary works such as formworks. Figure 2.5 shows that two persons work together to set out by means of a Total Station, with one sighting and the other marking on the floor.

![Figure 2.5 Setting out by means of a Total Station](image)

Setting out can be divided into horizontal setting out and vertical setting out. For horizontal setting out, gridlines are often used. As shown in Figure 2.6, there are
three types of gridlines, namely, orthogonal, non-orthogonal gridlines and radial gridlines. Setting out can be done by offset methods when using the former two types of gridlines. Polar setting out should be used when working under radial gridlines.

Methods of ensuring vertical alignment includes (Bell, 1993):

- Spirit level. This is effective for plumbing columns and formwork up to a height of one storey.
- Plumb bobs. These give a visual indication of the vertical when used in a suitable situation. The best conditions are a wind-free environment with a heavy bob immersed in a liquid to dampen the pendulum effects.
- Two theodolites. These are placed away from the building in positions where they can check vertically in two directions at right angles to each other.
- One theodolite employing a diagonal eyepiece. The optical plummet is used to set above a mark. The diagonal eyepiece makes it possible to view through the telescope when the telescope tube points vertically upwards.
- Optical plumbing device (auto plumb). This is a tripod-mounted instrument which produces a vertical sight upwards and one downwards, and automatically levels itself when the instrument is approximately level.
- Laser light. Many laser instruments can be adjusted to project the red laser light vertically up or down. In most conditions the practical range is limited to around 60m.
- Plumbing devices.
Vertical alignment of a building means transferring points from lower levels to upper levels of the building. Generally, in a building project, setting out is done respectively for the foundation, the ground floor and the upper floors. As each floor is added a new datum should be established directly above the datums on the floors beneath. Measurements to column centres should be referred to the new datum to ensure verticality as the building progresses. Generally speaking, to ensure vertical alignment, people can use two theodolites or the auto plumb. Figure 2.7 shows a method to ensure the vertical alignment of tall buildings.

One practical method to establish a good grid system for each floor level is to use the auto plumb internally at three or preferably four points as shown in Figure 2.7. This requires that holes be placed in each floor directly above the ground reference marks. A transparent plastic sheet in a frame shown in Figure 2.7 is placed above each hole in turn and intersecting lines of a chinagraph pencil mark on the plastic can provide a target. When the target is accurately located the frame is partially screwed down until a final check is made. Final adjustment, if necessary, is made by a slight tap with a hammer and then the frame is screwed down. To check the verticality of walls or columns the auto plumb may be set up externally at a distance $d$ from the edge and checked at each floor level using the external frame shown in Figure 2.7.

Also, a vertical alignment system, MOUS-System is widely used in building construction in the Netherlands. Figure 2.8 shows its principle of transferring points from lower level to upper levels.
Figure 2.7 Vertical alignment of tall buildings: a practical method
Setting out should be done with respect to a reference. The reference is the origin from which measurement is made. References are of two forms, either marks or points belonging to a neighbouring object. Therefore, in terms of the reference, setting out can be divided into mark-based setting out and object-based setting out. References can be in one, two or three directions. Therefore there exist 1D, 2D and 3D reference points, as shown in Figure 2.9. Reference points set out by the Total Station are in the X and Y directions, thus they are 2D points. By means of the Total Station, one can set out points that are more meaningful for positioning objects.

Figure 2.8 Vertical alignment with the MOUS-System
References are composed of points; marks are points themselves. Therefore, in essence, setting out is to define the positions of points. It must be known in advance which points should be set out and the answer should be found in the setting out plan.

2.3.3 Assembling

Assembling is a combination of positioning and fastening. The final position of building components or formwork parts, which are termed as objects, can be reached in several ways. When assembling an object, people don’t bring the whole object to a certain position, but bring several important points of that object to the position. Position is a relative concept. When assembling objects, people must relate their points with certain positions termed as references. References must be set out in advance. Also, the reference must be compared with special points of the component to be assembled. These special points are termed positioning points. A positioning point can be defined as “a point of an object that must be put in a certain position with respect to a reference." The amount of positioning points depends on, amongst others, the amount of freedom degree, with respect to the position of an object, which can be distinguished in the space. For a bending-stiff and torsion-stiff object, there are six freedom degrees, as shown in Figure 2.10. Three freedom degrees have relationship with the movement or translation of a point of the object in the space; the other three have relationship with the rotation of the object in a three-dimensional coordinate system.

When assembling a completely stiff object, at least three points should be brought into position. An example is shown in Figure 2.11. In this example, two points are used for positioning in three and two directions respectively, and the third point for positioning in only one direction. In practice, most objects are assembled by
giving the correct position to their points only in one direction. Therefore, the amount of positioning points reaches six. This amount can still be increased, if, for example, the concerned object is not stiff enough. The exact amount of points depends on the demanded dimension accuracy.

A positioning point must also be accessible in order to be related to a corresponding reference. Take a prefabricated column as an example. Its four corner points and four side middle points can be used as positioning points in practice.

Two positioning ways can be distinguished, namely, free positioning and forced positioning. Therefore, there exist free assembling and forced assembling, as shown in Figure 2.12. Free positioning can be defined as the combination of measuring and positioning an object; forced positioning can be defined as positioning an object in a forced way, by means of, e.g., a template or a guiding device. Figure 2.13 shows an example of free positioning and forced positioning as well as the positioning points concerned. You can see that corner points will be used for forced positioning, and middle points will be used for free positioning.
When positioning, the reference can be in several forms, as explained in the following:

(a) one or more marks, for example, in the form of a pencil line. These marks are formed by setting out. Positioning on the basis of marks is termed as mark-dependent positioning.

(b) one or more object points that constitute a neighboured object in the form of either realized building component or formwork.

(c) one or more object points that constitute the object to be assembled. This is a form of object dependent positioning.
One can position partially an object, either free positioning or forced positioning, in more advanced ways, when Total Stations with automatic target recognition feature are available. For example, one can put reflectors on the top of a column, and the Total Station can track it automatically. See Figure 2.14.

After the component has been positioned correctly, it must be fastened to the neighbouring components.

Again, positioning an object is indeed defining the positions of points. It must be known in advance which points should be used for positioning. The answer should be found in the assembling plan.

### 2.4 DESIGNING THE PLAN OF DIMENSIONAL CONTROL

The purpose of dimensional control is to meet the predefined dimensional quality. The requirements that are put on the dimensional quality of a building can be technical quality, esthetical quality and the combination of these two. Dimensional control is concerned with the whole activities including predicting, realizing and
monitoring the dimensional quality. Figure 2.15 shows the scope of the dimensional control.

The objective of making a dimensional control plan is to meet the prescribed accuracy standards as accurately as necessary, and as inaccurately as possible, in view of accuracy-cost relation, to minimize the cost and to be acceptable in labour circumstance.

![Diagram showing the scope of dimensional control]

2.4.1 Predicting Dimensional Quality

In building construction, three types of measures can be distinguished, namely, setting out measure, positioning measure and product measure. The setting out measure can be defined as the distance between a mark and the reference point. It is the result of setting out process. The positioning measure can be defined as the distance between a positioning point and the reference point that is held against when positioning an object. The product measure can be defined as the
characteristic measure of building products. It includes length, breadth, height and so forth.

Dimensional deviations are the differences between actual values and ideal values. Dimensional deviations cause consequences in a building’s functioning and cost. Deviation limits reflect dimensional quality of a building. Therefore, it is very important to predict dimension deviation limits when making a dimensional control plan. Dimensional deviations originate from two reasons, namely people handling and environment influence. The building construction process can be considered as a stochastic process with respect to statistics. Within the whole process, each separate production process will cause dimensional deviations. These separate deviations will propagate and add up to one another. In this way, deviation limits can be calculated.

2.4.2 Designing the Plan

The dimensional control plan is designed on the basis of building drawings and specifications delivered by architects. Figure 2.16 shows the designing process. First, a conceptual plan can be designed. The conceptual plan must fit within the whole conceptual construction plan.

When making an assembling plan, one needs to plan how the building components are positioned and fastened, and predict corresponding deviations. In other words, the following questions should be answered:
(a) which points of an object are positioning points?
(b) which points are referred by positioning?
(c) which points can be used by free positioning, and which can be used by forced positioning?
(d) which equipments are used, and what procedures are followed to measure, in the case of free positioning?
(e) which ways of dimensional correction can be used to reduce dimension deviations?
(f) in which ways and with which equipments can exact position be maintained temporarily?
When making a setting out plan, one needs to plan how a building is set out horizontally and vertically, and predict corresponding dimension deviations. In other words, one should decide that which points either of building components or formworks need to be set out, in what ways, and by which equipments. He or she also should calculate dimension deviations of these points.

When making a tolerance plan, one allocates the tolerance for product measure, setting out measure and positioning measure.

Figure 2.16 Designing a Dimensional Control Plan
After conceptually designing the assembling plan, the setting out plan and tolerance plan, the predicted dimension deviation limits of must be in accordance with the tolerances specified in conceptual tolerance plan. Then the final assembling plan, setting out plan and tolerance plan can be worked out.

Dimension monitoring is another process in the dimensional control process. The execution of monitoring measures can happen from various viewpoints, but the ultimate purpose of it is to ensure or improve the dimensional quality. This can be done internally by the contractors or externally by the inspector or independent institute depending on the purpose of the dimension monitoring. To execute the task of dimension monitoring, a plan of dimension monitoring should be designed. This plan is closely related with the tolerance plan, setting out plan and positioning plan.

When making a plan of dimension monitoring, one should decide that, which points of an object can be chosen and monitored during the construction process, and which points can be checked after the construction process, in order to achieve prescribed accuracy. Upon other three plans, i.e. assembling, setting out and tolerance plan, the final dimension monitoring plan can be worked out.

2.5 THE RESEARCH PROBLEM

The essence of designing a dimensional control plan is to make an assessment of all the points needed and their related information, and decide which points should be chosen, for different purposes, such as setting out, assembling building components and temporary works like formworks, and monitoring the dimensional accuracy. The points and related information can then be transferred into a Total Station. Figure 2.17 shows an example of the setting out plan.

Designing the dimensional control plan is a complex task. The designers must interpret the drawings, make an inventory of points needed, select appropriate points for different purposes and often add them to the drawings. When designing the plan, a lot of factors, such as prescribed accuracy and construction methods etc., should be considered. The designing process is in fact a decision-making and knowledge engineering process. Also, the plan varies from project to project, and
from designer to designer. Therefore, one of the objectives of our research is to study all the factors involved and their influence on the decision-making. Such kind of knowledge can be obtained by integrating theoretical principles and experiences of experts. This research therefore tries to capture such knowledge and make it available in a tool (Dimensional Control System, DCS) that supports designers of dimensional control plans.
Figure 2.17 An example of the setting out plan
**CURRENT SITUATION OF DIMENSIONAL CONTROL**

*This chapter starts with investigating the current situation of dimensional control in building construction in the Netherlands by studying standards, analysing the fragmentation in the process of building design and construction, and conducting site surveying. It is concluded that there is a lack of explicitly structured knowledge that can be used as a basis for designing the dimensional control plan.*

**3.1 INTRODUCTION**

As stated before, this research tries to capture and apply some knowledge that is needed for designing the dimensional control plan. This chapter is an effort towards that goal. First, this chapter studies and describes the current Dutch Standards for Measures and Measuring in Construction. It also depicts a picture of the fragmentation of the building design and construction process. Then surveying has been conducted on 21 building sites in the Netherlands, which includes observations on construction sites and interviews with site personnel including project managers, construction engineers and workers. Based on the surveying, several forms of building process contracts, including traditional contract, building team and design & construct, have been discussed, and current process of setting
out, positioning and fixing elements has been described. It is concluded that there is a lack of explicitly structured knowledge for designing the dimensional control plan that provides necessary information for the construction process.

3.2 INVESTIGATION OF RESEARCH PROBLEM

As steps towards capturing knowledge, this section studies the Dutch standards for measures and measuring in construction (NEN series 14), and also describes findings on the construction site.

3.2.1 Standards

In the NEN-series 14, the standards for measures and measuring in construction, which are specified by the Dutch Normalization Institute (NNI), NEN 2881, 2886, 2887, 2888 and 2889 are related to the dimensional quality. As shown in Figure 3.1, NEN 2886 is about the maximal allowable dimensional deviations in the (finished) buildings. It is therefore related to the end result. On the contrary, NEN 2887, 2888 and 2889 are related to the separate measures, respectively, setting out measures, positioning measures and product measures (prefabricated concrete). Figure 3.1 shows the relationship between partial results and end results.

![Diagram showing the relationship between partial results and end results](image)

Figure 3.1 Relationship between partial results and end results (Hoof, 1997)
In NEN 2886, the relationship among setting out measures, positioning measures and product measures is also defined. As shown in Figure 3.2, the concept “place tolerance” is defined as the tolerance related with the place of a point of the building part. It is calculated according to the formula 3-1. According to this method, the place tolerance of each point in the construction work can be calculated. The place tolerance doesn’t have much use in the practice because the desired place of a point is usually not pointed out in the building. What is more used in the practice is the position of points in respect to each other. In formula 3-2, the deviation of the position of two points in respect to each other is calculated.

\[ T_e^2 = T_i^2 + T_u^2 + T_i^2 \]  \hspace{1cm} (3-1)

\[ D=\frac{1}{2}\sqrt{( T_e1^2 + T_e2^2 + 8l)} \]  \hspace{1cm} (3-2)

You can see the deviation \( D \) depends on the place tolerances \( T_e \) of point1 and point2, and also the distance \( l \) between these two points.

In NEN 2881, terminologies and general rules related to dimensional tolerances for the building industry are described. The tolerance is defined as the difference between the upper limit (biggest allowable dimension) and the lower limit.
(smallest allowable dimension). The difference between the upper limit and the ideal dimension is defined as the maximal allowable positive dimension deviation; and the difference between the lower limit and the ideal dimension is defined as the maximal allowable negative dimension deviation. The adding up of tolerances is calculated by the formula 3-3:

\[ T_{\text{total}}^2 = T_1^2 + T_2^2 + T_i^2 \]  

(3-3)

NEN 2887 defines the maximal allowable dimensional deviations for setting out on the building sites. The maximal allowable dimensional deviation is equal to half of the tolerance \((D=T/2)\). The maximal allowable dimensional deviations for the distance should not be greater than \(\sqrt{l(16+2l)}\), where \(l\) is the distance between the measuring points.

NEN 2888 defines the maximum permissible dimensional deviations for the erection of load bearing structures of buildings. The standard makes distinction between sheet form and rod form elements, and also between horizontal and vertical orientation.

NEN 2889 defines the maximum permissible dimensional deviations for the concrete components. See Table 3.1.

For more information on NEN standards, the reader can refer to the publication of Netherlands Normalization Institute.

3.2.2 Building Process Contract Forms

Chapter 2 has shown generally the process of building design and construction. It also should be noticed that there are different parties involved in this process, namely architects, engineers, specialists, contractors and so on. These parties can form different kinds of working contracts, such as traditional contract, building team, and design & construct. Figure 3.3, 3.4 and 3.5 shows respectively the traditional contract, building team, and design & construct. Table 3.2 compares these three types of contract forms.
Table 3.1 Maximum allowable dimension deviations

<table>
<thead>
<tr>
<th>Product</th>
<th>Dimension</th>
<th>Form</th>
<th>Accessories</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>length</td>
<td>width</td>
<td>thickness</td>
</tr>
<tr>
<td>columns</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>mm</td>
<td>mm</td>
<td>mm</td>
</tr>
<tr>
<td>beams: &lt;=10m</td>
<td>-</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>NPS;</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt;=10m PS;</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&gt; 10 m PS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>truss form</td>
<td>11</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>elements</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>floor slabs:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NPS</td>
<td>28</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>PS</td>
<td>28</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>TT</td>
<td>21</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>walls</td>
<td>11</td>
<td>-</td>
<td>7</td>
</tr>
<tr>
<td>facades – inner</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>walls</td>
<td>7</td>
<td>-</td>
<td>5</td>
</tr>
<tr>
<td>stairs</td>
<td>14</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>balconies</td>
<td>7</td>
<td>7</td>
<td>5</td>
</tr>
</tbody>
</table>

NPS: non pre-stressed
PS: pre-stressed
TT: double T floor slabs
Figure 3.3 Traditional Contract

Figure 3.4 Building Team
As seen from Figure 3.3, 3.4, 3.5 and Table 3.2, the traditional contract form separates the design and construction, which causes separate responsibility, increases construction risks and delivers bad quality. It also hinders the cooperation between various parties and causes the discontinuity of ICT infrastructure, which is a barrier to apply DCS. The contract form of Building Team is an improvement, but the responsibility of design and construction, and the liability are still separated. The form of Design & Construct is the best suitable one because of its integration in all aspects.

Knowledge management is also an issue. Everybody involved in the building design and construction process, especially the architect, needs to go through a learning cycle in regard to dimensional control, which will promote the constructability of design. A long-term coalition will provide such a knowledge learning and management environment.
Table 3.2 Comparison of three types of contract forms

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Contract Forms</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Traditional</td>
</tr>
<tr>
<td>Responsibility for design &amp; construction</td>
<td>separate</td>
</tr>
<tr>
<td>Possibility to reduce construction risk</td>
<td>bad</td>
</tr>
<tr>
<td>Possibility to reduce performance risk</td>
<td>average</td>
</tr>
<tr>
<td>Liability</td>
<td>client for the total project, architect &amp; advisors for design/advice, relation tuning</td>
</tr>
<tr>
<td>Quality</td>
<td>bad</td>
</tr>
<tr>
<td>Integration of design &amp; construction</td>
<td>no</td>
</tr>
<tr>
<td>Complexity of building project</td>
<td>average</td>
</tr>
</tbody>
</table>

3.2.3 Current Situation of Dimensional Control on Building Sites

To investigate the current situation of dimensional control, 21 building sites have been visited in the Netherlands. Observations of the setting out and positioning of prefabricated structural elements have been done. In the meantime, interviews have been carried out with site personnel including project managers, construction engineers and workers. Table 3.3 shows the site locations and the types of each separate structural element. Table 3.4 shows the list of questions put forward to the site personnel. During the observations and interviews, the building elements have been studied in three directions, namely, height, depth and length direction. Figure 3.6 shows the whole process of bringing the prefabricated concrete elements to certain positions.
Table 3.3 Observation of different types of prefabricated structural elements on 21 building sites in the Netherlands

<table>
<thead>
<tr>
<th>Code</th>
<th>Location</th>
<th>Wall</th>
<th>Floor</th>
<th>Beam</th>
<th>Column</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>17</td>
<td>Voorburg Wilma</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>04</td>
<td>Maasland</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>11</td>
<td>Moerdijk Shell</td>
<td></td>
<td>1</td>
<td>1</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>08</td>
<td>Leiden</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>25</td>
<td>Utrecht</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>06</td>
<td>Helmond Adriaans</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>Voorburg BN</td>
<td>1</td>
<td></td>
<td></td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>03</td>
<td>Den Bosch</td>
<td>1</td>
<td>1</td>
<td></td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>02</td>
<td>Den Bosch</td>
<td></td>
<td></td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>06</td>
<td>Helmond Adriaans</td>
<td></td>
<td>1</td>
<td></td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>Zwolle</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>18</td>
<td>Venlo</td>
<td></td>
<td></td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>Barneveld</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>Utrecht</td>
<td>1</td>
<td></td>
<td></td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>Hengelo</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>05</td>
<td>Nijmegen</td>
<td>2</td>
<td></td>
<td></td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>Heerlen</td>
<td>1</td>
<td></td>
<td></td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>Maastricht</td>
<td></td>
<td></td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>Helmond NBM</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>Naaldwijk</td>
<td>1</td>
<td></td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>Venlo</td>
<td>1</td>
<td></td>
<td></td>
<td>1</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Total</strong></td>
<td>17</td>
<td>9</td>
<td>8</td>
<td>11</td>
<td>45</td>
</tr>
</tbody>
</table>

From the observations and interviews, some conclusions can be drawn on dimensional control for the building and each separate element. Although Total Stations are being widely used, traditional measuring instruments are still in use. The positioning methods include free positioning and forced positioning, with the latter as a majority. Whenever a building is higher than 30 meter, the main control point for the horizontal setting out work always consists of a MOUS-point. Also, the MOUS system is sometimes applied in lower buildings.
<table>
<thead>
<tr>
<th>Question</th>
<th>Answer</th>
<th>Amount</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>What do the positioning points consist of?</td>
<td>Surface of the element</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Supply in the element</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Marks on the element</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Poured in plate</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cover for bolt</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Where have the positioning points been brought?</td>
<td>In the factory</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>On the building site</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Not applicable</td>
<td></td>
<td></td>
</tr>
<tr>
<td>What do the reference points consist of?</td>
<td>Marks</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Template (positioned, unchangeable)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Template (positioned, changeable)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Neighbouring construction</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Own surface</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Template (not positioned, unchangeable)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pencil line</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Chalk line</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Nail</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Wood/block</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Bolt</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Piece on the bolt</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Piece on demu-anker</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Neoprene block</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Wood/block</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tile</td>
<td></td>
<td></td>
</tr>
<tr>
<td>What is the positioning method?</td>
<td>Forced positioning</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Free positioning</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Which correction methods are used?</td>
<td>No correction</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Individual deviation</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
For the columns, when positioning in the height direction, all are forced positioning; when positioning in the length and depth direction, most (80%) are free positioning because marks are set out; when plumbing, all are free positioning; the reference points for plumbing are the surface of the element with levelling instrument.

For the walls, the positioning points consist of, in almost all cases and for all three directions, the own surface of the element itself. The reference points exist in a variety. For the height direction, high and low buildings have been distinguished. For a high building (>30m), in which the accuracy plays an important role, there exists always a help device, which has been positioned in height with the help of a levelling instrument or laser. Whenever a building is not higher than 20 meter, mostly the neighbouring construction work or a non-positioned help device (a distance keeper) will be the reference. For the depth direction of the underside of the element, mostly the beneath construction work will be the reference. For the plumbing of the above side in the depth direction, apart from the parapet/breast wall, the own surface of the element itself is always used as reference. The reference points for the positioning in the length direction, consist of a marking or the surface of the neighbouring construction work.

For the beams, it is not specially set out in the horizontal plain, but the elements already positioned are used as the help device; for the height direction, sometimes it is set out with the normal instruments such as levelling instrument and laser; on the element itself nothing is set out. There is no distinction between temporary positioning and definite positioning, and the beams are put on their place in one go. There are minimal six points used for positioning. The positioning points consist of the own surface of the element. Only in depth direction is positioning measure correction used. It is a correction on the basis of individual deviation. Whenever the correction is used, one or two extra positioning points are used.

For floor slabs, in 90% of the cases, there is nothing set out on the elements. There is never positioning measure correction used. The required accuracy is low. In the height direction, the reference points consist of the neighbouring construction work, and the way is forced positioning; the floor slab is definitely positioned by
the gravity. In length direction, the floor is definitely positioned by friction. In the depth direction, the floor slab is also definitely positioned by friction and positioning points consist of the surface of the element.

In Figure 3.6, you can find the process of setting out, positioning and fixing elements. The working equipments, information needed for each stage and information flow between each stage are all depicted in this figure. In essence, the basic information needed is the positioning ways, positioning points and corresponding reference points which should be set out in advance. All these kinds of information should be actually found in the dimensional control plan. Therefore, it is very important to give the right information in the plan. To design such a plan, the engineers must consider a lot of aspects. However, from the interviews and observations, you can feel that most engineers design such plans and choose positioning points and corresponding references just according to experiences without explaining the reason. There is a lack of explicitly structured knowledge.

3.3 CONCLUSIONS ON DIMENSIONAL CONTROL

In the beginning, one of the research objectives has been to investigate the body of knowledge used by the engineers to design the dimensional control plan. After observations on building sites and interviews with the engineers, contractors and site personnel, it is concluded that there is little explicitly expressed knowledge generally available. That is to say, there are no clear answers to the question of which points to be used for the different aspects of dimensional control including setting out, positioning and dimension monitoring and why. Also, in the NEN standards, the answer cannot be found though it gives some insight to tolerances and deviations.

The dimensional control problem is basically of a stochastic nature, because every measure originating from construction process has a stochastic deviation and each solution first has to find a way to handle this.
To summarize, the following conclusions on dimensional control can be drawn:

1) There is, as yet, very little dimensional control knowledge available that has been formally expressed;

2) There is a lot of factual dimensional control knowledge that resides quite – in the form of rules of thumb – in the heads of experienced planners;

3) There are so many forms of deviations and dimensional differences following different construction methods for various types of projects, that it is not reasonable to expect that the whole body of dimensional control knowledge will ever be fully formalized at all;

4) Handling the stochastic deviations originating from construction processes like prefabrication, setting out and positioning, is quite problematic for humans but ideally suited for computers.
Figure 3.6 SADT schema: bring the prefabricated concrete elements to certain positions
ANALYSIS OF THE STATE OF THE ART INFORMATION TECHNOLOGY RELEVANT FOR DIMENSIONAL CONTROL IN THE BUILDING INDUSTRY

Information and Communication Technology (ICT) has been playing an important role in the building industry. This chapter gives a brief analysis of some leading technologies that are relevant for dimensional control.

4.1 INTRODUCTION

Application of ICT in the building industry started somewhere in the 1960s with do-it-yourself programming in BASIC. Simple algorithmic programming was ideal for the early days when often differential equations had to be solved by hand. Structural engineering was the subject most suited to the technology of that time. In later years, when centralised computers gave way for PCs, a wide variety of commercial applications came into being. Some of the underlying technologies
most relevant for dimensional control will be reviewed below. The main areas that have to be looked into are:

- Logical connections of the floor plan design to the Dimensional Control (DC) application that will be developed as part of this study;
- Physical connection, i.e. the standards used for electronic data exchange;
- Knowledge Technology;
- Graphical User Interfaces;
- Programming languages and environments.

The next sections discuss these topics in more detail.

4.2 BRIDGING DESIGN AND DIMENSIONAL CONTROL

There are several ways that designers and engineers can represent their designs. These ways range from traditional paper-based approaches to product modelling. Each approach has its consequences for this study. For each approach, the available possibilities and exchange standards are also looked into.

4.2.1 Paper-based Approach

The obvious consequence of using traditional paper-based design-drawings is that the Dimensional Control System (DCS) envisioned in this study cannot pick up the required design data in electronic form. The user of the DCS has to input all the data himself. This calls for a tool that resembles an existing building modeller. Getting the required design data in house is no problem. Just rely on the postman and take your time.

4.2.2 Computer Aided Drawing (CADr)

Computer Aided Drawing or Drafting (CADr) systems, starting from 2D modelling techniques in the 1960s, are capable of representing objects mathematically in the computer. A wire-frame model is the simplest and most verbose type of 2D model. In the 1970's, the 3D wire-frame was subjected to 3D translation and rotation, giving greater illusion of solidity, relieving users from the burden of interpreting 2D drawings. Over the past years, the development of solid
modelling systems enabled a wide range of applications to be modelled in 3D, including mass properties, volumes and moments of inertia.

CADr (Computer Aided Drawing or Drafting) systems have been widely used in the building construction industry. CADr systems concentrate on the production of traditional technical drawings. CADr drawings have advantages over traditional physical drawings. Amongst others, CADr drawings can be reused to make design and drafting efforts more efficient; CADr drawings can be easily changed to accommodate design modifications and additions; CADr systems layer design information for efficient editing, viewing and plotting; CADr systems plot complex shapes and give accurate dimensions for construction layout (Mahoney, 1990).

CADr systems are able to create the geometrical representation of building objects, and allow the addition of more semantic information as needed for input into the data model. Therefore their inherent structure to classify data has to be used in a standardized manner. Methods to structure CADr data are classified into layers, macros and attached attributes. Layers are mainly used to control visibility. In addition, they offer the possibility to group sets of data, such as all load-bearing walls of ground floor. Many CADr systems still restrict the use of layers in such a way that any entity is only allowed to be a member of one particular layer. Macros can be used to label and control all geometric entities, which are representations of one building element. Macros thus offer grouping mechanisms on the instance level, which is necessary to keep unique identifiers for the bi-directional exchange of meaningful descriptions of building elements. Attached attributes are mainly used to store non-geometric information on entities or macros, such as the material, the building code and optional explanations.

**Shortcomings of current CADr**

Until now, CADr systems are still used mainly as a drawing tool, though some attempts have been made to extend their functionality with meaning and intelligence. This is due to the inherent bottlenecks of CADr systems (Liebich, 1995). First, almost all conventional CADr systems rely on a pure geometric data model consisting of lines and points. All non-geometric information about objects
has to be attached to these geometric entities. This restricts the ability to describe semantically dependant relationships. In the real architectural and engineering design process the representation of design objects is context dependant. Second, the data exchange remains restricted since it is based on a fairly low semantic level of document based exchange of information, the level of technical drawings, such as geometric representation in DXF or IGES, rather than on a high semantic level of a model based exchange. Third, although CADr systems offer a programming interface, they require advanced programming skills, much effort, and time to bring knowledge or additional information into systems. Even so, systems still often have low performance. Thus CADr systems are not intelligent. CAD systems have limited achievements due to the deficiencies of their underlying database.

CADr systems have drawbacks also in presentation techniques. The CADr database is the prime source of design information. However, the majority of current CADr packages provide users and developers alike with only one view, i.e. the entity view, which represents the raw CADr data as an unordered set of graphical primitives such as points, lines, and arcs. Software vendors' primary goal is to optimise the performance of their CADr packages, as a drawing tool, through the employed method of data storage. Meanwhile, a users' view of the drawing model in building elements format, is not accounted for. This constitutes a major obstacle for the acceptance of a free flow of information between CADr systems and other applications packages used by professionals in industry. Furthermore, geometry alone is limited in its usefulness for driving the some applications packages where other non-geometrical information is required. New CADr systems support both element representation and non-geometrical data. However, these systems define elements by tagging the geometry with labels. As a result the object integrity is not maintained. Clients' limited ability to visualize 2D design solutions usually lead to misinterpretation of the design. This problem has been partially overcome by animation techniques in which 3D images (frames) can be rendered and generated to simulate 3D walkthroughs. The limitation imposed by the predefined animated paths, the high cost of reproducing the animated images, and the inability to interact with these images has not helped designers/clients to fully solve this problem.
Data exchange standards

There are several standards available for the exchange of drawing files. AutoCAD’s DXF and DWG are the two standards most often used. One problem here is that both standards are vendor dependant (AutoDesk) and not completely platform independent and error free. Several projects report problems with using these standards in practice.

Other standards are developed by STEP (see below) and ISO. None of these standards is used in the building industry.

Conclusions on CADr and DC

Though it is technically possible to import the DXF/DWG drawing files and reconstruct the elements (columns, beams, walls) of the floor plan from the available data, it is not possible to do that in general without an industry wide layering and mark-up convention. If the designers are willing to adopt a layering and mark-up convention for the purpose of dimensional control, it seems possible to extract the DCS input automatically from the drawing files.

CADr is a typical example of the common innovation process. Just like the first motorcar strongly resembled the horse wagon, CADr systems strongly resemble the drawing board. Subsequent development cycles show and eliminate the shortcomings inherited from the past, in this case the need to build a 3D model from points and lines only.

4.2.3 3D Geometric Modelling

3D geometric modelling extends the notion of points and lines with faces, volumes and primitives shapes. 3D geometric modelling does not play the same role in the building industry as in other sectors of industry, like Mechanical and Automotive. In those sectors Constructive Solid Geometry (CSG), Boundary representations (B-rep) and surface modelling are often used. In our sector only one special type of B-rep called Cellular model, or Relational Model plays (RM-rep) a role.
**RM-modellers**

The RM-rep was for instance used in the COMBINE-project (Augenbroe, 1993 & 1995). The essence of an RM-rep is (i) that it starts with Spaces that are enclosed by Faces (or face sides) and (ii) that it includes relations like point-on-a-line, point-on-a-face, face-on-a-face, etc. This makes the RM-rep particularly suited for building design.

If the design of a floor plan has been described with an RM-modeller it is also known which lines and faces represent which elements and consequently extracting the input required by the DCS is not too big a problem. Unfortunately standards for data exchange of RM-rep data do not exist, so a general connection to different systems cannot be implemented.

**4.2.4 Product Data Technology**

Product Data Technology (PDT) has been introduced in the 1980s. Basically the ideas follow the concept of feature modelling used by the designers of mechanical parts in the automotive industry. A feature is a small area of a part with ‘engineering meaning’ (Shah). Examples are holes, pockets, ribs and such. Essentially a feature does not require any further design; given its parameters, everything is known, including the way to produce the feature. Mechanical engineers design their parts by designing and dimensioning the required features.

PDT in the building industry also attempts to design a building by designing and dimensioning semantic entities. However in our industry we want to design a building by dimensioning and placing walls, floors, beams, columns etc. So the features of the Mechanical engineers became the walls, floors, beams and columns of the architects and structural engineers.

This section evaluates some of the Information Technologies that are important for PDT.

**Product Modelling**

Product modelling aims at the production of a generic data description for a particular product domain - a “universe of discourse”, for actors within that
domain - containing ‘complete’ and unambiguous information about a product (building). Complete in the sense that all information required for a specific application, if available, will be specified as an integral part of the product model or can be derived from it (Gielingh, 1990). In the case of building design systems, it aims at producing generic information models for various categories of buildings (Ramscar, 1995). A data model provides the basic tools for describing the data types, relationships and constraints of the information stored in a database, expressed in documents or in speech. An analogy would be the basic grammar utilized in natural language (Bjork, 1991). Thus, a building product data model defines generic data types and relationships (“product grammar rules”) encapsulating the kinds of objects that will be instantiated within the building domain (Ramscar, 1995).

The product model comes into being to meet the trends towards integration. In the late 80s a product model was defined in (Vajna, 1991) as a model, consisting of geometrical model as well as some other models, for instance:

- Procedural models (consisting of instructions for building element production);
- Topological models (consisting of relative position of the geometrical elements);
- Method models;
- Technological methods (dimensional and location tolerance, tasks for creating surrounding surface, information texts about production methods).

More general and abstract is the following definition (Junge, 1993): Product modelling aims to describe unambiguously all the objects with their attributes and relations, which range the solving task.

Construction is a process that involves diverse parties having different professional skills and intersects. Drawings, standard methods of measurement, building specifications and standard forms of contract are all paper-based models that provide formalized methods of communication (Munns, 1995). Open integration of computer applications in construction requires true product descriptions rather than 3D models or 2D drawings (Bakkeren, 1997). That is
because only meaningful descriptions can contain all relevant product information in a computer interpretable way; three dimensional models contain information on a limited set of product aspects only, usually geometry; two dimensional drawings contain even less product information interpretable by computer. The latter two are meaningful to human beings only.

The future intelligent applications ‘know’ the information they process and can therefore interpret this information, maintain its consistency and derive other information from it without human intervention. Since these applications understand product descriptions and posses encoded domain knowledge they can even augment the creativity and knowledge. Integrating these intelligent applications requires meaningful product descriptions. Computer integration based on geometric models can never reach the level that is possible with meaningful product descriptions.

Product data technology (PDT) is the technology directed at the definition, use and management of meaningful product information in computer-integrated processes. Product modelling is that part of PDT that focuses on defining meaningful product descriptions in a computer interpretable way. The physical realization of a product model is a shared database, an exchange file or any other way of computer interpretable storage of information. A product model can first be defined in generic level, and then be instantiated.

Open application integration requires that all applications can read and write information in a standardized format and assign the same standardized meaning to this information. The format used for exchange is usually referred to as the syntax. The meaning of the information is usually referred to as the semantics. Syntax is often associated with file exchange, but not limited. A data dictionary defines the words that can be used to describe information on semantics. It is an equivalent to the term “ontology” in the field of artificial intelligence. Olsen et al. (Olsen, 1995) defines ontology as “a dictionary of classes, relations, functions and object constants along with their definition in human readable text and machine interpretable sentences”.

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There are some general-purpose product modelling systems primarily for building design. Examples are AutoCAD Architectural Desktop, Allplan, ArchiCad and Speedikon. These systems often have an internal format for storing building information and several modules that can use that format. Most of the systems still use a 3D geometry model as the core of the building information. Other non-geometric information is attached to this three-dimensional model and often stored in a database that is separated from the geometry model.

Conclusions on PDT

PDT undoubtedly is a key technology for ICT in construction. The problem is the implementation in our industry. PDT requires (1) standardisation of the formats, (2) implementation by the vendors, (3) adoption by the industry and (4) application in real life projects. This process takes a lot of time and effort. Other industries with strong industrial market leaders, like aerospace and automotive have made much more progress than the building industry.

STEP (STandard for the Exchange of Product model data)

STEP (STandard for the Exchange of Product model data) is an emerging international standard (ISO 10303) for representing and exchanging product model information. It includes an object-flavoured data specification language, EXPRESS, to describe the representation of the data. The data model is graphically represented by EXPRESS-G. STEP defines also implementation methods, for instance, a physical transfer file, and offers different resources, e.g., geometric and topological representation.

The development of STEP started in 1984 as a worldwide collaboration. The goal was to define a standard to cover all aspects of a product (i.e. geometry, topology, tolerances, materials, etc.), during its lifetime. STEP is a collection of standards to represent and exchange product information. The main parts of STEP are already international standards, while many parts are still under development. The development is performed under the control of the International Standards organisation (ISO), Technical Committee 184 (TC184, Industrial Automation
The objective of STEP is to offer system-independent mechanism to describe the product information in computer aided systems throughout its lifetime. It separates the representation of product information from the implementation methods. Implementation methods are used for data exchange. The representation offers a definition of product information to many applications. STEP provides also a basis for archiving product information and a methodology for the conformance testing of implementations.

EXPRESS is a formal data specification language used to specify the representation of product information. The use of a formal data specification language facilitates development of implementation. It also enables consistency of representation. STEP specifies the implementation methods used for data exchange that support the representation of product information.

STEP does not only define the geometric shape of a product, but also includes topology, features, tolerance specifications, material properties, etc. necessary to completely define a product for the purposes of design, analysis, manufacture, test, inspection and product support. The use of STEP is still very modest but it is growing all the time. The majority of CAD system vendors have implemented or are implementing STEP pre- and post-processors for their CAD systems. STEP is an evolving standard that will cover the whole product life cycle in terms of data sharing, storage and exchange. It is the most important and largest effort ever established in engineering domain and will replace current CAD exchange standards.

Conclusions on STEP

STEP is not yet important for the building industry, though several STEP parts may well be used with advantage, notably the Express modelling language, the resource schemas and in the future the STEP equivalent of the IAI/IFC (see next section).
Industry Foundation Classes (IFC)

The International Alliance for Interoperability (IAI) is committed to creating a standard to enable true interoperability among all of the players - and the software they use - who are involved throughout the life cycle of a building.

As of this writing the IAI has over 300 member companies in seven international chapters, and is growing daily. Its vision is to enable software interoperability in the AEC/FM industry; its mission is to define, promote and publish a specification for sharing data throughout the project life-cycle, globally, across disciplines and across technical applications; it is a not-for-profit industry organization and its membership is open to any company working in the AEC/FM industry.

The intention of the IAI is to define all of the objects that could occur in a building (such as doors, windows, walls, and so on). Then, define a specification for how each object will be represented electronically. These specifications are called Industry Foundation Classes (IFC). Together they represent a data structure supporting an electronic project model useful in sharing data across applications.

The IFC require that each object has known characteristics. It is more than a simple collection of lines and geometric primitives. An object is stored and manipulated in a manner consistent with the designer’s intent. IFC-based objects allow all AEC/FM professionals to share an underlying building information model, yet allows each profession to define its own view of each of the objects contained in that model; the objects designed by an architect can later be used by other professionals. This leads to improved efficiency in cost estimating, building services design, construction, and facility management.

IFC enable interoperability among AEC/FM software applications. Information modelling in IFC is based on EXPRESS-G. The classes can be used by software developers who are familiar with object-orientated programming methods to create applications that use universal AEC/FM objects based on the IFC specification. An object created in one application can communicate with another IFC-compliant application. This second application recognizes the object and is able to understand these characteristics and add information to the object, because it also uses the IFC specifications defined by the IAI. Applications that support IFC will
allow members of a building project team to share data (such as drawings, reports, and specifications) in an electronic format. This will ensure that the data is consistent and coordinated. Furthermore, this shared data can continue to evolve after design, through construction, and occupation of the building. Information generated by the project design team will be available in intelligent, electronic format to the building construction team through their IFC compliant software and to building facilities managers through their IFC compliant software.

Several product modellers such as Allplan and AutoCAD Architecture Desktop, can already read and write IFC 1.5 shape representations. However, exchange of product model data is cumbersome because the required attributes have to be derived from the neutral geometrical model. In the Brite-Euram CONCUR-project these ‘derived attributes’ will be standardised.

Conclusions on IFC
The Industry Foundation Classes are becoming the default standard for product modelling in the building industry. Most vendors of Building Design Systems support IFC. When the current shortcomings are eliminated in the future, IFC will be of great benefit.

4.3 KNOWLEDGE TECHNOLOGY
This section looks into the applicability of Knowledge Technology for the development of a Dimensional Control System.

Knowledge Technology (KT) is what in the old days was called Artificial Intelligence (AI). Intelligent computer systems that use certain design principles (like separating the knowledge part and applying a knowledge engine) are called Knowledge Base Systems.

4.3.1 Background and Definition
A knowledge based system (KBS) is a software system capable of supporting the explicit representation of knowledge in some specific competence domain and exploiting it through appropriate reasoning mechanisms in order to provide high level problem solving performance. Therefore, a KBS is a specific, dedicated,
computer based problem solver, able to face complex problems, which, if solved by man, would require advanced reasoning capabilities, such as deduction, abduction, hypothetical reasoning, model based reasoning, analogical reasoning, learning, etc. (Guida and Tasso, 1994).

Knowledge in this context is a technical word. It covers for example the content of building regulations, codes of practice, all kinds of algorithmic and procedural knowledge (as implemented in analysis systems), as well as less well-defined experience-based knowledge, or very precisely defined knowledge found in predicative logic, or propositional logic.

For the purpose of this study the main focus is on the knowledge that plays a role in DC.

4.3.2 Importance for the Building Industry

Construction and Dimensional Control is very much a business of experience, expertise, and good judgment. Expert systems could capture and broadly disseminate the knowledge of scientists and experienced consultants in this area. The main reason for trying to apply KT and specifically, expert systems to construction is to deal with the qualitative and judgment-based types of problems that are prevalent in this industry. In the case of DC the main problems are (1) place of control points, (2) place of Total Station, (3) handling of deviations.

Experience and knowledge of experts can be captured in computer programs so that other construction engineers and managers can access it and apply it, perhaps even after the experts who provided the knowledge are no longer available. Such programs also provide a means to integrate and validate the knowledge and experience of many experts and thus provide a means for accumulating and improving a body of knowledge over time.

There are different types of knowledge, each requiring another representation. Figure 4.1 shows a matrix that tries to classify the field according to two parameters: “Data Intensive” and “Degree of Difficulty”. Data Intensive classifies the representations according to the amount of data that can be processed, and Degree of Difficulty classifies the representations according to the amount of
knowledge and the way the knowledge is known (well defined, weakly defined, and undefined). The horizontal classification distinguishes between *deductive* reasoning (where the relations between input and output are well known) and *inductive* reasoning, where the relations between input and output are less well known or even unknown.

![Diagram of knowledge representation classification](image)

Figure 4.1 Classification of knowledge representations. The vertical axis groups the representations according to the amount of data that can be processed. The horizontal axis groups the representations according to the amount and preciseness of the knowledge that plays a role. The application of formal logic, for example, is useful for problems with relatively little data and a small amount of well-defined knowledge.

For the “Data Intensive” categories such as Data Mining, there are typically many dimensions (up to several hundreds) and many data points (many thousands or even millions). Dimensional control is not a problem that requires the processing of such a large amount of data, so its representation belongs to one of the three groups at the bottom of the matrix.
Along the Complexity axis dimensional control is less easy to classify. It is partly a problem with well-defined knowledge (if all the measurement points are well defined and the measuring equipment is able to view each point). In that sense it belongs to the left group where modelling and simulation seem representations of interest. However dimensional control also involves elements of stochastic uncertainty that places it in the middle group. And finally DC also involves circumstances where people base their decisions solely on experience, without being able to explain why they make these decisions. This might place the DC problem partly in the right group. In the next sections these three groups will be investigated somewhat deeper.

For the development of the DCS and the formalization of measurement control experience, the most important knowledge technologies seem to be:

- Simulation
- Rule Based Systems
- Fuzzy Logic
- Inductive Knowledge (Neural Networks, Genetic Algorithms and Case Based Reasoning)

Simulation

Determining the best position for the measurement control points and the place of the Total Station is largely related to the prediction of dimensional deviation limits. This can be done by simulation techniques. Numerical methods that involve sampling from random numbers are called Monte-Carlo Methods. Monte-Carlo simulation is often used in risk analysis and problems involving statistic or stochastic variables. As dimensional control is a problem covered by stochastic deviations with uncertainty, Monte-Carlo simulation seems an attractive technology.

Rule Based Systems (RBS)

RBS are particularly suited to problems involving expert reasoning. RBS typically store heuristic knowledge in a rule base. The facts are generally stored in the form of “IF-THEN” rules. The RBS use the rules as they are needed to solve problems
when presented with data. As measurement control knowledge in most cases can be expressed as rules of thumb RBS seem to be most applicable for DC.

**Fuzzy Logic**

Fuzzy Logic is interesting if linguistic ambiguity comes into play, like in the following rules:

**IF** distance_measurement is *LONG*
**THEN** deviation_accuracy is *LOW*

To make use of these rules both parameters *LONG* and *LOW* must be formalized, i.e. how small is small and how low is low? This type of problems can be tackled with fuzzy sets (i.e. the sets LONG and NOT-LONG) and membership functions that express the degree of membership of a variable of both sets.

Linguistic ambiguity always plays a role in the building industry, so probably also in DC.

**Inductive Knowledge (Neural Networks, Genetic Algorithms and Case Based Reasoning)**

Representations in this group aim to learn to predict improved solutions from experience. Neural Networks mimic the working of the brain. In a Neural Network system the relation between a small set of inputs and outputs is formed by a network of nodes with weights that can either stimulate or suppress its contribution to the solution.

Artificial neural networks can be most adequately characterised as “computational models” with particular properties such as the ability to adapt or learn, to generalise, or to cluster or organise data, and which operation is based on parallel processing.

An artificial network consists of a pool of simple processing units that communicate by sending signals to each other over a large number of weighted connections.
A neural network has to be configured such that the application of a set of inputs produces (either “direct” or via a relaxation process) the desired set of outputs. Various methods to set the strengths of the connections exist. One way is to set the weights explicitly, using a priori knowledge. Another way is to “train” the neural network by feeding it teaching patterns and letting it change its weights according to some learning rule. Genetic Algorithm can also be utilised to optimise a neural network.

Neural networks are particularly effective for predicting events when the networks have a large database of prior examples to draw on.

Genetic Algorithms (GA) mimics the evolution of species and the principle of survival of the fittest. GA is one of the evolutionary algorithms (EA), which are used to describe computer-based problem solving systems that use computational models of evolutionary processes as key elements in their design and implementation. EAs all share a common conceptual base of simulating the evolution of individual structures via processes of selection, mutation, and reproduction. The processes depend on the perceived performance of the individual structures as defined by an environment.

More precisely, EAs maintain a population of structures, which evolve according to rules of selection and other operators, which are referred to as “search operators”, (or genetic operators), such as recombination and mutation. Each individual in the population receives a measure of its fitness in the environment. Reproduction focuses attention on high fitness individuals, thus exploiting the available fitness information. Recombination and mutation perturb those individuals, providing general heuristics for exploration. Although simplistic from a biologist’s viewpoint, these algorithms are sufficiently complex to provide robust and powerful adaptive search mechanisms.

The Genetic Algorithm is a model of machine learning that derives its behaviour from a metaphor of the processes of evolution in nature. This is done by the creation within a machine of a population of individuals represented by chromosomes, in essence a set of character strings that are analogous to the base-4
chromosomes that we see in our own DNA. The individuals in the population then go through a process of evolution.

Genetic Algorithms are used for a number of different application areas. An example of this would be multidimensional optimisation problems in which the character string of the chromosome can be used to encode the values for the different parameters being optimised.

Evolutionary Programming is a stochastic optimisation strategy similar to Genetic Algorithms, but instead places emphasis on the behavioural linkage between parents and their offspring, rather than seeking to emulate specific genetic operators as observed in nature.

Like GAs, EP is a useful method of optimisation when other techniques such as gradient descent or direct, analytical discovery are not possible. Combinatory and real-valued function optimisation, in which the optimisation surface or fitness landscape is “rugged”, possessing many locally optimal solutions, are well suited for Evolutionary Programming.

Neural network systems can help in the following situations:
- where it is impossible to formulate an algorithmic solution.
- where it is possible to get lots of examples of the behaviour as required.
- where it is necessary to pick out the structure from existing data.

GA is applicable for optimisation problems and requires that you can immediately qualify a solution, i.e. you should be able to say if a solution is better or worth than an earlier solution.

For the problem of dimensional control, the stochastic dimensional deviation variables are according to normal distribution. Each deviation variable is out of N(0, σ_i) and in the range of (-D_max, D_max). The D_max can be determined according to standards and σ_i can be approximated from samples. The value of D_max and σ_i can be optimised in order to generate random numbers that simulate the stochastic deviations as close as possible. And neural network can also be trained for this goal, mapping inputs consisting of measured data or observations of the stochastic
dimensional deviations of various sorts to output consisting of $D_{\text{max}}$ and $\sigma_i$. The appropriate network would be a combined one with data classification and mapping. Therefore neural network and genetic algorithm would help to optimise a random number generator in Monte-Carlo simulation.

To solve other problems where the relation between cause and effect is unknown (can not be explained), for example, if a surveyor always knows the best place for the Total Station, but is not able to explain why, you need a lot of examples to train the neural network. Unfortunately, right now there are no such examples available, therefore for this type of problem, it is only possible to apply NN in the future.

GA might also be used in situations of error propagation in the problem of dimensional control (DC). In DC, there are typical structural assembly situations. You can choose components with known deviations and analyse the total deviations. Then you can change components from the set of available components and predict which components to use where. GA seems interesting as an extension to analysing these situations.

In case-based reasoning (CBR) systems expertise is embodied in a library of past cases, rather than being encoded in classical rules. Each case typically contains a description of the problem, plus a solution and/or the outcome. The knowledge and reasoning process used by an expert to solve the problem is not recorded, but is implicit in the solution.

To solve a current problem: the problem is matched against the cases in the case base, and similar cases are retrieved. The retrieved cases are used to suggest a solution that is reused and tested for success. If necessary, the solution is then revised. Finally the current problem and the final solution are retained as part of a new case.

All case-based reasoning methods have in common the following process:

- retrieve the most similar case (or cases) comparing the case to the library of past cases;
• reuse the retrieved case to try to solve the current problem;
• revise and adapt the proposed solution if necessary;
• retain the final solution as part of a new case.

Case-based reasoning is often used where experts find it hard to articulate their thought processes when solving problems. This is because knowledge acquisition for a classical KBS would be extremely difficult in such domains, and is likely to produce incomplete or inaccurate results. When using case-based reasoning, the need for knowledge acquisition can be limited to establishing how to characterise cases.

Case-based reasoning allows the case-base to be developed incrementally, while maintenance of the case library is relatively easy and can be carried out by domain experts.

To apply CBR into DC field requires, in the first place, a database filled with cases (DC plans). There isn’t such a database yet; therefore, it is not yet feasible to apply CBR.

In conclusion, Neural Networks, Genetic Algorithms and Case Based Reasoning are able to capture experience where the relation between cause and effect is unknown (can not be explained). Also Neural Networks can be used for data classification and mapping inputs to outputs, and Genetic Algorithm can be used for optimisation. Conceptually, it is possible to apply these technologies if there exists a large set of data, examples, cases or a procedure that can quickly analyse the results of the chosen solution. Currently, as these requirements are not yet completely fulfilled, the application of inductive knowledge is not yet fully feasible, though it may come into play in the future. To apply these technologies, more research should be performed.

Conclusions on Knowledge Technology support for DC

For the development of the DCS, the Monte-Carlo simulation, the application of Rule Based Systems and Fuzzy Logic seem to be most important. Other technologies could be used to solve particular problems. For example, inductive
knowledge might become important in the future, and it might be possible to build more autonomous measurement control systems. For now, however, it seems that simulation, RBS and Fuzzy Logic are the most appropriate knowledge technologies for DC.

4.4 GRAPHICAL USER INTERFACES
Building a DCS that suites the end-users needs, will need decisions about the graphical user interface (GUI) that the user will have to work with. There are several aspects that have to be looked into, among others, the graphics, including Virtual Reality.

4.4.1 Virtual Reality (VR)
A Virtual Reality scene or ‘world’ is a simulation of a real or imaginary world, which a user can interact with. A VR world of a project provides designers, clients, suppliers, contractors, authorities and public with a common basis for communication that is widely available over the Internet. Designers can add the shapes of the design objects they create to the scene and make the information related to the design objects generally available by a mouse click.

The most important Internet-based VR language available is VRML.

VRML
VRML is an acronym for Virtual Reality Modelling Language. VRML, by use, is a 3D scene-description format that has plugs built in to provide networking and multi-user accessibility. It’s quite possible to create a VRML world just using a text editor. However, to build more complex scenes, modelling software will be required. There are different software packages that can create VRML worlds.

There are basically two types of VRML modellers: object builders and scene assemblers. An object builder enables the user to create arbitrary shapes interactively and then export the geometry in the VRML format. These packages usually support other 3D file formats as well. A scene assembler allows the user to assemble 3D objects into VRML scene, and include hyperlinks, inlines and Level-of-Detail.
There are also a number of different tools available for converting models from other commonly used 3D file formats (such as AutoDesk’s DXF and 3DStudio) into VRML. Some tools are programs freely available via the Internet.

VRML allows developers to create "virtual worlds" of arbitrary visual and geometric complexity, with the added feature of attaching WWW hyper-links to any object. These worlds are downloaded over the Internet just like any other file, and displayed in a VRML browser (such as WebSpace). VRML browsers are used in concert with a normal Web browser (such as Netscape), which provides a mechanism for viewing standard text and multimedia resources.

**VR versus CAD**

As mentioned before, CAD systems have drawbacks in presenting information. As VRML is generally available for free and able to combine output of many different modellers, the emerging VR technology complements the limitations of CAD.

**Conclusions on Virtual Reality**

The application of VR for Dimensional Control seems to be in the ‘world wide’ sharing and exchange of design information. As discussed above, the application of CAD systems and PDT systems rely on a process of standardisation, vendor implementation, company-adoption and project agreement, which is time consuming and cumbersome.

VRML on the other hand is basically an Internet technology that is generally available without special hardware requirements (though broadband Internet helps). If in the future project partners decide to create and maintain a common VR project scene, DC can also use the scene to extract the required information about each floor plan and to communicate the resulting details about the DC plan.

**4.5 IMPLEMENTING THE DCS**

There are several ways the Dimensional Control System can be implemented. Two broad divisions are obvious. First the systems can be implemented in Visual Basic or Java. Second the system can be built on top of, or strongly related to AutoCAD.
4.5.1 Visual Basic (VB)

Visual Basic is a Microsoft (MS) product. VB has the advantage that it integrates very well in the MS environment and with a large number of related systems and tools.

Visual Basic is an object-based programming language and system builder. The first step to creating an application with Visual Basic is to create the interface, the visual part of the application with which the user will interact. Forms and controls are the basic building blocks used to create the interface; they are the objects that a programmer will work with to build his application.

The programming language, a modern version of Basic, is an up to date and powerful language that is quite simple to understand and use.

Conclusions on VB

Microsoft VB is a widely available industry standard and, despite its simplicity, a powerful programming environment that suites the needs of the building industry.

4.5.2 Visual Basic for Applications (VBA)

Visual Basic for Applications is both a subset and a superset of VB. The two have lots in common but they differ in that VBA contains application-specific properties, methods and events. Every VBA-enabled application has its own object model. Typically, the programmer needs to add a reference to the application's type library in his project. From that point, he uses the VBA commands as if they were native to VB itself.

VBA is found as a component in AutoCAD and many Microsoft applications including Access and Excel. This provides a mechanism to integrate different applications.

Conclusions on VBA

Although VB is more powerful than VBA, VBA makes it possible to integrate AutoCAD with Microsoft applications such as MS Access and MS Excel in the DCS.
4.5.3 Java

Java is the preferred programming language of today. Using Java has some strong advantages. It is vendor independent, platform independent, nicely object oriented and well documented and available. Because of the very structured programming language in combination with the readability of the code, Java becomes a powerful tool for implementing complex and not so complex programs. Mastering Java however is much more difficult than mastering VB.

Conclusions on Java

For developing the DCS, Java has no particular advantages over Visual Basic. Java is much more difficult and largely inaccessible for casual programmers.

4.5.4 AutoCAD

AutoDesk’s AutoCAD is the leading computer-aided design and drafting (CAD) program in the world. In the building industry, AutoCAD is the default industry standard. Over the years, AutoCAD has kept pace with developments in the computer industry.

Conclusions on AutoCAD

As AutoCAD is so important in the building industry it is the prime candidate for implementing the DCS.

4.5.5 Architectural Desktop

AutoCAD’s latest product line is AutoCAD Architectural Desktop (ADT). ADT is developed mainly for architecture and building design. It embraces the potential of 3D model-based design and object-oriented software, without sacrificing any of the CAD productivity gains. ADT introduces basic building model objects so that all applications built for AutoCAD software or ObjectDBX™ can now share the same definition of these objects.

In addition, as discussed before, AutoDesk is a founding member of the International Alliance for Interoperability (IAI), an organization dedicated to sharing building model data across the building life cycle and to creating the IFC
(Industry Foundation Class) specification for model data exchange between CAD systems.

Conclusions on ADT
ADT seems quite capable and powerful for the job of implementing the DCS. However it is also still too advanced. Though the number of designers working with ADT is rapidly growing, its popularity is greatly overshadowed by AutoCAD. Also ADT has strong competitors, like ArchiCad and Allplan. ADT is not dominating the PDT-market and cannot be seen as a default industry standard.

AutoCAD VBA
AutoCAD VBA is a new development line of AutoCAD that uses the ActiveX Automation Interface to integrate AutoCAD with VBA. AutoCAD VBA permits the Visual Basic environment to run simultaneously with AutoCAD and provides programmatic control of AutoCAD. There are three fundamental elements that define ActiveX and VBA programming in AutoCAD. The first is AutoCAD itself, which has a rich set of objects that encapsulates AutoCAD entities, data, and commands. The second element is the AutoCAD ActiveX Automation interface, which establishes messages (communication) with AutoCAD objects. The third element is the VBA programming environment that has its own set of objects, keywords, constants, and so forth, which provide program flow, control, debugging, and execution.

Conclusions on AutoCAD VBA
The linking of AutoCAD, ActiveX Automation, and VBA provides an extremely powerful interface. A VBA application for AutoCAD is much faster than a VB application, because VBA application is in-process that means it works in the same address as AutoCAD, and VB application should communicate with AutoCAD by Inter Process Communication (IPC). The VBA API is integrated in AutoCAD and no additional software is needed to develop such an application, whereas Visual Basic is needed to develop a VB application. In addition, VBA is
also available in MS applications. Considering these facts, VBA is the primary candidate of programming language for implementing the DCS.

4.6 CONCLUSIONS

The previous sections discussed the state of the art in ICT as seen relevant for the development of a Dimensional Control System. The main conclusions are:

- **AutoCAD and Visual Basic** provide the development environment most suitable for DC. Besides the fact that AutoCAD is market leader in design software of the building industry, it also provides an entrance to the world of Product Data Technology and related next generation tools. With the integration of Visual Basic, a simple but powerful programming language and application builder, it seems possible to build a DCS that can be accessible for the future users to add their own experience to the system. VBA is the programming environment most suited to the job, as it is able to work with a domain specific object model. This object model can be tailored to the needs of DC. Moreover with ADT also a product-modelling interface (IFC) becomes available. Finally there are several ways to import and export VR.

- **Knowledge Technology**, especially Rule Based Systems, provides mechanisms suitable for DC to express engineering experience in the form of rules of thumb. Simulation and modelling are suited for prediction and calculation of error propagation of dimensional deviations. Fuzzy logic can be used to add greater flexibility to the expressions if linguistic ambiguity comes into play.
REFORMULATION OF THE RESEARCH QUESTIONS

This chapter summarizes the analysis of previous chapters and reformulates the research questions.

5.1 INTRODUCTION

In Chapter 1, it has been stated that, to improve the dimensional control of on-site construction projects, while focusing on prefabricated concrete building structural elements, this research (1) tries to capture the knowledge required to design an adequate dimensional control plan and make that knowledge more generally available and (2) build a digital connection between CAD systems and Total Stations.

The initial research questions have been formulated as follows:

- Is it possible to develop an ‘intelligent’ instrument that supports the less experienced planners to develop adequate dimensional control plans?
- How to facilitate the digital information flow between CAD systems and Total Stations?
After literature review, observation on construction sites and interviewing experts, it is concluded that there is very little explicitly structured and formalized knowledge available to be put in a knowledge base as a general solution to dimensional control problems. Dimensional uncertainty, dimensional deviation, and the stacking up of deviations springing from several sources form the core of the problem. On the other hand, it could still be possible to design a system capable of capturing rules of thumb when they come along.

Another observation has been that the DCS envisioned could also support experienced planners in complicated positioning situations. In fact the use of the DCS in complicated positioning jobs seems to be more attractive than the application of the DCS by inexperienced planners.

Finally the idea that it is mandatory to automatically input the design data into the DCS has been dropped. The reasons are:

- The fact that the DCS will most probably be mainly used (at least for a start) by experienced planners in complicated situations. In those cases inputting the required data is only a very small part of the job.
- Automatic information flows from CAD to DCS can be easily implemented using the IFC-format once it becomes the default industry standard, provided of course that the DCS is based on PDT-principles.

5.2 REFORMULATION

Based on the evaluations given in section 5.1 above, in this section, the research questions have been reformulated as follows:

- How to design and implement an ‘intelligent’ DCS that supports the planners to develop adequate dimensional control plans, and supports the site personnel to realize the requested dimensional quality?
- How to handle the dimensional deviations aspects of dimensional control problem?
- How to express some knowledge rules for dimensional control problem in addition to handling stochastic deviations?
SIMULATION OF DIMENSIONAL DEVIATIONS

This chapter presents a method and a model that can be used to simulate setting out deviations, positioning deviations and product deviations, and the prediction of the dimensional deviation limits that show the dimensional quality.

6.1 RECAPITULATING THE PROBLEM

In previous chapters, it is concluded that there is a lack of theory and knowledge that can be used as a basis for designing the dimensional control plan that provides necessary information for the construction process. This chapter starts to tackle the problem by looking into the aspect of dimensional quality of a building and its components. It presents a method to simulate setting out deviations, positioning deviations and product deviations, and the prediction of the dimensional deviation limits that show the dimensional quality. Also, some influencing factors for dimensional control have been added to this method. Then, using PDT principles, the Dimensional Control information model is defined using the Unified Modelling Language (UML).
6.2 PREDICTION OF DIMENSIONAL QUALITY

The essence of designing a dimensional control plan is to find out which points should be used as positioning points, which points should be set out in advance or controlled afterwards, and why. These questions are in fact, to a great extent, related to the aspect of dimensional quality. Therefore, one must be able to predict the dimensional deviation limits that show the dimensional quality. Also there are some other factors that influence the choice of choosing certain points, for example, the location and positioning method of an object, and the visibility of the positioning points. These factors will also be expressed in some knowledge rules.

In building construction, design or “ideal” dimensions and actual dimensions are distinguished. The architects give the ideal dimensions of building components in the drawing, and specify dimension tolerances in the specifications. The actual dimensions occur after components are produced, or during or after the construction of the building. The actual dimensions can never be the same as the ideal dimensions. The differences between these two are termed *dimensional deviations*. Deviation-limits reflect the dimensional quality of a building.

Also, in building construction, three types of measures are distinguished, i.e. the setting out measure, the positioning measure and the product measure. The setting out measure can be defined as the distance between a mark and the reference point being used. It is the result of the setting out process. The positioning measure can be defined as the distance between a positioning point and the reference point used for positioning an object. The product measure can be defined as the characteristic measure of building products. It includes length, width, height and so forth. See Figure 6.1.

Dimensional deviations originate from people handling, instrument accuracy and environment influences. For example, the measuring deviations come from persons who do the measurement; the measuring instrument has a system deviation coming from manufacturing; also the temperature changes can cause deformation of building components. The building construction process can be considered as a stochastic process with respect to statistics. Under certain circumstances, the construction process can be considered as a normally
distributed process. That is to say, if the value and frequency of a certain production process is put in a histogram, it is a normal distribution curve. Another statistical principle is that when more (independent, normally distributed) processes are put together, the combined process is also normally distributed.

![Figure 6.1 Basic elements causing place deviation of a point](image)

Therefore, predicting the deviation limit of each object requires considering the deviation as a result of chain-processes. Especially, the processes of prefabricating production, setting out and positioning should be taken into account. These three processes cause (1) **product deviation**, (2) **setting out deviation** and (3) **positioning deviation**. To calculate the final deviation they should be added together. The final “place deviation” which can be defined as the deviation related to the place of a point of the building part, is equal to the sum of these separate deviations.

Each object will be viewed as a collection of points. For the prediction of the dimensional deviation limits of each point of an object two methods can be used.
The first method recognizes the stochastic characteristics of each individual deviation; that is to say, each individual deviation is distributed according to a normal distribution. Then the total deviation is calculated according to the following formula:

\[ \Delta P_L^2 = \Delta P_R^2 + \Delta P^2 + \Delta S^2 \]  

(\( \Delta P_L \): Place deviation, \( \Delta P_R \): Product deviation, \( \Delta P \): Positioning deviation, \( \Delta S \): Setting out deviation).

Using this method, you need to know the value of each individual deviation in order to get the total deviation.

The second method assumes that each individual deviation belongs to a certain range that has a certain percentage of certainty. For example, the deviation can be within the range of \( \pm 10 \, \text{mm} \) with the certainty of 98%. Each deviation is randomly picked out of certain range and put together. If this is done a large number of times (e.g. 1000 times), the distribution of the total deviation can be predicted. This approach, following the Monte Carlo simulation technique, can be termed the simulation method.

The predicted dimensional deviation limits should be within the specified tolerances. Also, after predicting the dimensional quality, the predicted quality should be achieved following some procedures. This can be done by means of, among others, a combination of working methods that are statistically controlled processes. Otherwise, the prediction of dimensional quality will not be true or cannot be achieved. The working methods are related to setting out and positioning processes, and must be specified in the setting out plan and positioning plan.

6.3 SIMULATION OF DEVIATIONS AND REPRESENTATION OF KNOWLEDGE RULES

Determining various sorts of dimension deviations separately and then putting them together will make the simulation of concrete elements. Positioning
deviations, setting out deviations and product deviations are simulated respectively in the following sections.

### 6.3.1 Simulating Setting Out Deviations and Positioning Deviations

To position an object, minimum 6 1D points are needed to overcome the translation and rotation of the object. Using a set of points as positioning points will have influence on all the other points regarding the final place deviation. The simulation method is used to calculate the final place deviation. To find out the influence, it is better to first study the final place deviation of the origin of the object. Then the final place deviations of other points from the changed origin can be calculated.

As shown in Figure 6.2, to define the origin of the object with deviation, link the middle point of AD and BC; find the centre point of plane EFCH; then create the plane MIJ and define the origin that is its centre point.

![Figure 6.2 Defining the origin and positioning points of an object](image)

A: x, y, z direction;  
B: y, z direction;  
C: z direction;
The maximal allowable setting out deviation in x, y and z direction is respectively \( S_{x_{\text{max}}} \), \( S_{y_{\text{max}}} \) and \( S_{z_{\text{max}}} \) (with 98% certainty). The computer will choose a value randomly (with normal distribution) within these limits respectively for the setting out deviation in x, y and z direction, that is to say \( S_x \), \( S_y \) and \( S_z \).

The position of the origin of the element in regard to the origin of the building can be calculated by bringing the following steps: the translation of the origin of the building to the reference point, the translation of the reference point to a positioning point of the element, the translation of the positioning point of the element to the origin and finally the rotation of the element around the x, y and z axis.

The rotation of the x, y and z axis of the element in regard to the coordinate system of the building can be calculated by the rotation caused by the dimensional deviations in the positioning measures in regard to the coordinate system of the building, plus the rotation caused by the deviations in the product measures in regard to the coordinate system of element.

If an element in the building is positioned following the setting out points and positioning points, two different coordinate systems are put together, which are the coordinate system for the building and for the individual element. This requires a transformation of the element coordinate system to the building coordinate system.

To determine the position of points of an element in the building coordinate system, it is calculated as follows:

The translation of the origin of the building coordinate system and the origin of the element coordinate system;

The translation of the origin of the element and the point itself;

The rotation in x, y and z direction of the element coordinate system.

This means that, to determine the rotation around z-axis, two x or y positioning coordinates that lie in the same surface are needed. Accordingly, the similar goes for the rotation around x or y axis. See Figure 6.3.
Choosing a set of positioning points has consequences on all the points. The final place deviation of each point is seen as a result of the product deviations, the setting out deviations and positioning deviations of the selected points. Each of these three kinds of deviations will result in three translations and three rotations of the object.

Figure 6.3 Rotation around each axis of the element

In Figure 6.4, a simulated situation of rotations in three directions has been drawn. In this simulation, the object first has a rotation around Z axis, which results a new X axis and Y axis; then the object has a rotation around the new X axis, which results a new Z axis; finally the object rotates around the new Y axis. Following these three steps, a point \((X,Y,Z)\) will get a new position \((X_3,Y_3, Z_3)\). Figure 6.4 shows the projection of each rotation respectively seen from the third positive axis.

The matrix \(R_z\), \(R_x\) and \(R_y\) respectively shows the rotation around Z, X and Y axis. The final position \((X_3, Y_3, Z_3)\) of the point is calculated by formula (6-5).

\[
R_z = \begin{bmatrix}
\cos \alpha & \sin \alpha & 0 \\
-\sin \alpha & \cos \alpha & 0 \\
0 & 0 & 1 \\
\end{bmatrix}
\] (6-2)
R_x = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \beta & \sin \beta \\ 0 & -\sin \beta & \cos \beta \end{bmatrix} \tag{6-3}

R_y = \begin{bmatrix} \cos \gamma & 0 & -\sin \gamma \\ 0 & 1 & 0 \\ \sin \gamma & 0 & \cos \gamma \end{bmatrix} \tag{6-4}

\begin{bmatrix} X_3 & Y_3 & Z_3 \end{bmatrix} = [X \ Y \ Z]R_z \times R_x \times R_y \tag{6-5}

Figure 6.4 Simulated rotation of the object in three directions

6.3.2 Simulating Product Deviations

For the simulation of product deviations, floor slabs, beams, walls and columns are all characterized by their rectangular form and consist of 6 surfaces, 3 symmetry axes and further 8 conceptual corner points and 12 edges. It is termed “conceptual” because in fact corner points and edges don’t exist. They are always in more or less measure rounded off.
To orient, a coordinate system has been chosen in which the X, Y and Z direction is in accordance with the width, the thickness and height direction of the element respectively. The origin is the centre gravity point of the element.

Each surface is defined by 9 (grid)points. See Figure 6.5. In fact, the number of points doesn’t matter. The principle keeps the same for either more or less points. It matters however for the accuracy, that is to say, the more points, the more accurate. The middle (grid)point is coincident with the cutting point of the surface with an axis of the coordinate system. The other points are equally divided so that the distance to the edge \( r \) of the element in each case is same. It will show that at the end the dimension deviation of these points is perpendicular to the surface.

![Figure 6.5 Defining a surface by 9 grid points](image)

The element is now defined by \( 6 \times 9 = 54 \) points. For the simulation, the element is divided in 3 separate segments. Each segment consists of 2 either opposite or parallel surfaces, combined with each other by one of the axes of the coordinate system. For the clarity, a column is drawn as an example in Figure 6.6, but it can also be a wall, beam or floor element.

Now consider randomly 2 parallel surfaces of the element, connected by one of the axes of the coordinate system, the so-called connection axis. Assume that the deviation in the direction of the connection axis of the 18 points on these 2 parallel surfaces is zero and bring the various sorts of deviations in the direction of the connection axis in calculation for these points.
For a three dimensional object, one can distinguish the various sorts of deviations also in three dimensions. The following deviations are valid for a segment of the element:

1 Dimensional: The distance between the opposite surfaces, measured along the connection axis, characterized the dimensions (length, width, height or thickness) of the element. A deviation on this distance moves itself along the line of the connection axis.

2 Dimensional: The direction of the surface in regard to the connection axis, is determined by 2 randomly unparalled lines, which lie in the surface. The cutting point of the surface and the connection axis can be viewed as a spherical hinge point around which the surface can rotate. A deviation on the direction of the surface characterized the (un)perpendicularity of an individual surface in regard to the connection axis and the (un)parallelness of the surfaces with respect to each other.
3 Dimensional: The form of the individual surface. Due to the deviation in the flatness of the surface, it is a 3 dimensional object. The surface is in fact not a surface. The unflatness is caused by deviations that can be characterized as curvature and warp.

The above-mentioned deviations are defined as the characteristics of the individual element and will be simulated by determining them individually and then adding them on top of one another. The segment that consists of the under surface, the Z axis and the top surface is graphically illustrated as an example. The principles that apply to this segment are also valid for the other two segments.

**The distance between the opposite surfaces: 1D product deviation**

By dimension of the element, it means actually the length, height, thickness or width of the element. Here the dimension of the element is defined as the distance perpendicular to and between 2 parallel surfaces at which the cutting points of these 2 surfaces with the connection axis serving as measuring points. The distance between the under surface and the top surface of the element is thus defined by the length of the Z axis between the cutting points of the under surface and above surface with this axis. The deviation on this distance is determined by a random number, which is distributed according to normal distribution, and can be considered as a constant deviation that is valid for both surfaces. For the nominal distance \( A \), it is defined that the maximal allowable deviation \( a_{\text{max}} \) mm (98% certainty) may be carried. Whenever the computer randomly chooses a value \( a \) within this limit, then the top surface and the under surface gets a deviation of \( 0.5a \) respectively seen from the origin. The points in the surface all get therefore the same positive or negative deviation of \( 0.5a \) in the direction of the connection axis. See Figure 6.7.

**The direction of the surface: 2D product deviation**

It means by the direction of the surface in fact the direction of the surface in regard to the connection axis. For the under surface and the top surface, the Z axis is the connection axis. A deviation in the direction of the surface can be described by the unperpendicularity of the individual surface and the (un)parallelness of both surfaces in regard to the connection axis.
If a plane independent from the opposite plane gets a deviation in connection with the direction of the plane in regard to the connection axis, this is called the unperpendicularity of the individual plane. The unperpendicularity can be defined as a variable deviation of the individual plane. The plane can take each direction. The unperpendicularity of the under plane and the top plane can be expressed in the X direction and Y direction. The unperpendicularity of the individual plane is defined by two random numbers that are distributed according to normal distribution. The maximal allowable deviation for the unperpendicularity of the under plane and top plane in the X and Y direction is defined respectively as $h_{xmax}$ and $h_{ymax}$ mm/m (98% certainty). Whenever the computer chooses randomly two values ($h_x$ and $h_y$) within these limits, the plane gets an unperpendicularity of these two values. For two opposite planes, four independent numbers are chosen. The points in a plane all get an unequal positive or negative deviation in the direction of the connection axis as a result of the unperpendicularity of the involved plane. Figure 6.8 shows how the various deviations in the Z direction for the points in the under plane or top plane interrelates.
The (un)parallelness of two opposite planes is analog to the unperpendicularity of two opposite planes. This is concerned with a deviation in the direction of both planes in regard to the connection axis. The (un)parallelness can be considered as a constant deviation of the opposite planes. The planes can take each direction. The (un)parallelness of the under plane and top plane can be expressed in the X and Y direction respectively. The (un)parallelness of these opposite planes is defined by two random numbers that are distributed according to normal distribution. The maximal allowable deviation for the (un)parallelness of the under plane and top plane in the X and Y direction is defined respectively as $e_{x_{\text{max}}}$ and $e_{y_{\text{max}}}$ mm/m (98% certainty). Whenever the computer chooses randomly two values ($e_x$ and $e_y$) within these limits, the plane gets a (un)parallelness of these two values. For two opposite planes, two independent numbers are chosen that are valid for both planes. The points in these planes all get an unequal positive or negative deviation in the direction of the connection axis as a result of the (un)parallelness of the involved planes.

Figure 6.8 2D product deviation: unperpendicularity and (un)parallelness
The form of the plane: 3D product deviation

The form of the individual plane depends on the deviations in the flatness of the plane. It means by the unflatness of the plane in fact the measure in which the points don’t lie mutually in a plane. The unflatness is independent on the coordinate system. The surface is in fact not a surface, but a 3 dimensional object. By randomly choosing 3 gridpoints on the surface that don’t lie on a line, one can define a reference surface. The bigness of the spreading of the distance in the direction of the connection axis of the other gridpoints to this reference surface is a measure for the unflatness. The unflatness is caused by deviations that can be distinguished as the curvature and warp of the plane.

The curvature of a line or a surface can be defined by its length and the radius of the belonging circle or sphere. Regarding the curvature of a segment of the element, three types have been considered, namely the common curvature of both surfaces, the curvature of the individual surface and the curvature of a gridline of the individual surface.

Figure 6.9 Common curvature
Figure 6.9 shows the common curvature of two opposite surfaces. It can be considered as a constant deviation that is valid for both surfaces and is defined in two directions. For the under surface and top surface, the curvature is expressed in the X direction and Y direction respectively, and is defined by two random numbers that are distributed according to normal distribution. For the curvature of the under surface and top surface, the maximal allowable deviation in the X and Y direction may have $k_{z,x,max}$ mm/m and $k_{z,y,max}$ mm/m (98% certainty) respectively. Whenever the computer chooses randomly two values ($k_{z,x}$ and $k_{z,y}$) within these limits, then these surfaces get a curvature with a result of these two values. For two opposite surfaces, two independent numbers are chosen that are valid for both surfaces. All the gridpoints in the opposite surfaces, except the cutting point with the connection axis, get therefore an unequal positive or negative deviation in the direction of the connection axis as a result of the common curvature.

The curvature of the individual surface can be considered as a variable deviation of both surfaces and is defined in two directions. For the under surface and top surface, the curvature is expressed in the X direction and Y direction respectively. The curvature of the individual surface is defined by two random numbers that are distributed according to normal distribution. For the curvature of the top surface, it is defined that the maximal allowable deviation in the X and Y direction may have $k_{z1,x,max}$ mm/m and $k_{z1,y,max}$ mm/m (98% certainty) respectively. Whenever the computer chooses randomly two values ($k_{z1,x}$ and $k_{z1,y}$) within these limits, then the top surface gets a curvature with a result of these two values. Similarly, for the curvature of under surface, whenever the computer chooses randomly two values ($k_{z2,x}$ and $k_{z2,y}$) within the limits of $k_{z2,x,max}$ mm/m and $k_{z2,y,max}$ mm/m (98% certainty) respectively, the under surface gets a curvature with a result of these two values. For two opposite surfaces, four independent numbers are chosen that are valid for the curvature of both surfaces. All the gridpoints in a surface, except the cutting point with the connection axis, get therefore an unequal positive or negative deviation in the direction of the connection axis as a result of the curvature of the individual surface. See Figure 6.10.
Figure 6.10 Curvature of individual surface

The curvature of a gridline of the individual surface can be considered as a variable deviation of all gridlines. Each surface has six gridlines and the curvature of a few gridlines of the individual surface of a segment is defined in one direction. This means that there is more curvature in one direction within an individual surface. For the under surface or top surface, the curvature of a few gridlines is expressed in either the X direction or the Y direction. The curvature of a gridline in a surface is defined by a random number that is distributed according to normal distribution. For the curvature of a gridline in the top surface or under surface, it is defined that the maximal allowable deviation in the X and Y direction may have $k_{z;1;x,max} \text{ mm/m}$ and $k_{z;1;y,max} \text{ mm/m}$ (98% certainty) respectively. Whenever the computer chooses randomly a value ($k_{z;1;x}$ or $k_{z;1;y}$) within these limits, a few gridlines get a curvature from which the most outside gridpoints on this line get a positive or negative deviation in the direction of the connection axis. For two opposite surfaces, 12 (6 in each surface) independent numbers are chosen that are valid for the curvature of the gridlines in both surfaces. All gridpoints in a surface, except the cutting point with the connection axis, get therefore an unequal
positive or negative deviation in the direction of the connection axis as a result of the curvature of the gridlines in the individual surface. See Figure 6.11.

![Figure 6.11 Curvature of gridline](image)

The warp of a surface can be defined by the measure in which 4 points don’t lie in a plane. The plane is in more or less degrees tortured. Warp can be measured by an imaginary plane drawn by three random corner points. The distance between the fourth corner point and the corner point of the imaginary plane is a measure of the warp. See Figure 6.12. By dividing the warp over 4 corner points, you will find no warp within the original plane. This plane creates the starting point for the simulation of the warp. For the warp of the plane of a segment, the common warp of both planes and the individual warp are considered.
The common warp of two opposite planes can be considered as a constant deviation that is valid for both planes, and is defined by a random number that is distributed according to normal distribution. For the warp of the under plane and above plane, it is defined that the maximal allowable deviation may carry $s_{z,\text{max}}$ mm (98% certainty). Whenever the computer randomly chooses a value ($s_z$) within this area, these planes will get a warp that is distributed over 4 corner points. One number is picked and valid for both two opposite planes. All gridpoints in the opposite planes, except the cutting point with the connecting axis, get thus an unequal positive or negative deviation in the direction of the connecting axis as a result of the common warp. See Figure 6.13 (left part).

The warp of the individual plane can be considered as a variable deviation of both planes and is defined by a random number that is distributed according to normal distribution. For the warp of the above plane, it is defined that the maximal allowable deviation may carry $s_{z1,\text{max}}$ mm (98% certainty). Whenever the computer randomly chooses a value ($s_{z1}$) within this limit, then the above plane will get a warp that is distributed over 4 corner points. Similarly, for the warp of the under plane, whenever the computer randomly chooses a value ($s_{z2}$) within the maximal allowable deviation $s_{z2,\text{max}}$ mm (98% certainty), the under plane will get a warp that is distributed over 4 corner points. For two opposite planes, two independent
values are therefore picked that are valid for the warp of both planes. All gridpoints in a plane, except the cutting point with the connecting axis, get thus an unequal positive or negative deviation in the direction of the connecting axis as a result of the warp of the individual plane. See Figure 6.13 (right part).

Figure 6.13 Common warp and individual warp

For the form of the surface, there are more characteristics such as straightness and warp to be considered. Also there can be more directions for the curvature of the surface. However, apparently the parameters given in the above have a satisfied simulation of the practice.

The tolerance concerned with 1 grid point
In this simulation method, the coordinates of each grid point of each concrete element in respect to the origin of the building are known. The place deviation of each grid point should be compared with the place tolerance. The place tolerance is the tolerance concerned with the place of a point of the building part in respect to the desired place. It should be noted that in the practice, people do not check whether the place tolerance is exceeded, because the desired place of a point in the building is not often defined, and usually the maximum allowable dimensional deviation between two physical points is used on building sites. In the simulation, however, the place tolerance is used. The place tolerance is the area that symmetrically lies in respect to the desired place of a point of the building part.
6.3.3 Expression of Knowledge Rules
Some influencing factors for dimensional control of building components are discussed in this section. First, the positioning method of a component influences the choice of positioning points. If a component is positioned using free method, one needs to consider the location of the component. For example, if a column is located on the edge or corner of a floor, its corner points can’t be used as positioning points for the horizontal positioning. If a component is positioned using forced method, then the location doesn’t matter. Also if the component is positioned using direct positioning in 3D, then the visibility of its positioning points seen from the Total Station should be taken account. These are some example rules for dimensional control of building components and will also be modelled in the UML information model.

6.4 THE UML MODEL

Figure 6.14 on page 90 shows the Dimensional Control information model in UML. The Appendix at the end of the thesis gives a simplified description of the UML syntax.

What the model says is that a Floorplan limits the scope of the Dimensional Control view. Floorplan describes the relevant physical objects of a floor in a World Coordinate System (WCS). A WCS is a Coordinate System defined by an Origin and X, Y and Z-axis all defined as 3D vectors, where 3D vector is defined by an X, Y and Z value.

Each Floorplan has one Main Control Point, which is a 3D-Point. Each 3D-Point has X, Y, and Z-values and a Name or Number. A Floorplan consists of a set of Typical Structural Assemblies.

A Typical Structural Assembly has a World Coordinate System of its own, and consists of several Positioning Objects.
A Positioning Object (a physical object that has to be positioned) is either a **Structural Element** (like a Beam, Wall, Column, Facade or Slab), or **Formwork**. Each Positioning Object refers to an **Object Coordinate System (OCS)** that can be transformed to WCS, and has an **Origin**. A **Rectangular Box** with a **Height**, **Width** and **Length** value represents a Positioning Object. A Positioning Object has an **ID** and one or more **Positioning Points** that are again 3D Points. A Positioning Object also has the attribute of **Location** that can be on the **edge**, **corner** or **middle** of a floor. A Positioning Object has also **Positioning Method** that can be either **Free** or **Forced Positioning**. A Positioning Object has also the operation of **Translate**, **Rotate** and **Set Positioning Method**.

Positioning Points can be **selected** or **not**. Positioning Points also have the operation of **Set Visibility** that sets the attribute of **Visibility** to **True** or **False** according to **angle**, **light** or **other factors**. Positioning Points have **Product Tolerance**, **Setting out Tolerance** and **Positioning Tolerance**. Positioning Points refer to **Reference Points**, which are 3D-Points. Reference Points refer to **Setting out Points** and Setting out Points refer to Main Control Point. Positioning Points have **Setting out Deviation**, **Positioning Deviation** and **Product Deviation**. Product Deviation can be 1D, 2D and 3D. **1D Deviation** includes the deviation in Length, Width and Height. **2D Deviation** includes **Unparallelness** and **Unperpendicularity**. **3D Deviation** includes the deviation of **Curvature** and **Warp**.

### 6.5 CONCLUDING REMARKS

The Dimensional Control information model structures the entities or objects needed for both the simulation of dimensional deviation limits and expression of engineering experience. Also example knowledge rules have been incorporated to the objects. This model is open and more knowledge rules can be added when available.

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1 The subtypes of Positioning Object in the model are in fact only examples; other objects can be handled just as well.
Figure 6.14 Dimensional Control Information Model in UML
SYSTEM DESIGN AND IMPLEMENTATION

This chapter proposes a computer-aided system for dimensional control based on the model presented in Chapter 6. It starts with defining the system requirements, followed by the system functional design; then the system is implemented by prototyping; finally some concluding remarks are given.

7.1 DEVELOPMENT OF A COMPUTER AIDED SYSTEM FOR DIMENSIONAL CONTROL

In order to improve the dimensional quality of on-site construction projects, this chapter proposes to develop a support tool that fits into the current trend of using standardized electronic product models as the main carrier of construction information. Figure 7.1 shows the proposed system and its overall environment.

Basically the idea of this support tool is that a project database holds a detailed description of the facility under construction in a “neutral” (vendor independent) product model format. A product model described in the neutral format describes a facility (building, road, bridge) in the semantics of the construction industry. Product models can be exchanged or accessed by computer networks.
Figure 7.1 Structural elements in the Real System are positioned using a Total Station. The Total Station is fed with control data produced in the Information System by the DC-Tool.

For the Building and Construction industry, currently the most promising product model format candidate is the format developed by the International Alliance for Interoperability (IAI) called the Industry Foundation Classes (IFC). (Refer to Chapter 4 for more on IFC). This format is already available for several Design systems, like Speedikon, Allplan and AutoCAD Architectural Desktop.

To improve the dimensional quality of a project by applying Product Data Technology, the project database is filtered and converted by the Dimensional Control tool (DC-Tool) to a local database that describes the facility as a collection of physical objects (structural elements, equipment and temporary structures) accompanied by coordinate systems and setting-out points. Next the positioning points are defined on the physical objects, using reference points, and the deviation and tolerance data is analyzed. The DC-Tool feeds the required control data to the Total Station on the construction site.
7.2 SYSTEM DESIGN AND IMPLEMENTATION

7.2.1 System Requirements

The system should function as follows:

1. The user chooses a typical structural assembly and inputs parameters like the length, width and height of each element representation. The system can also read AutoCAD drawings if they are in IFC format, otherwise if in other format like plain AutoCAD drawing, the system can only open them and then special converter needs to convert point, line and arc into IFC format objects.

2. The system displays the chosen typical situation or extracts structural objects from the drawing, generates a collection of points and asks the user to select certain positioning points of an element.

3. The user clicks certain points and the system predicts the deviation limits by putting together all kinds of product deviations, setting out deviation and positioning deviation as well, and also gives the possibility distribution of deviation limits.

4. The system advises the user on selecting positioning points according to the prediction results and checking of some relevant knowledge rules regarding the visibility of points, positioning methods and location of building components. If the deviation limits are within the prescribed tolerances, these points are recommended; otherwise, choose some other points. Sometimes, if the prescribed tolerance is too small, the system might suggest enlarging it.

5. The system will add setting out points, reference points according to the selected positioning points.

7.2.2 Implementation Environment and Approach

To design the application tool, first the software environment should be chosen. As analyzed in Chapter 4, the system can be strongly related with AutoCAD environment. With the development of CAD systems and product data technology, AutoCAD Architectural Desktop introduces the IFC utility and has some intelligent objects such as walls, columns and openings. It can thus read and write IFC file partially. AutoCAD also introduces the concept of exposing AutoCAD objects through an ActiveX interface and programming those objects using Visual
Basic for Applications programming environment. Therefore, AutoCAD Architecture Desktop, Access and Excel have been chosen as the software platform, and VBA as the programming language to implement the model.

AutoCAD objects and AutoCAD ADT (Architectural Desktop) objects have been used to implement the graphical objects in the model, such as wall, window, opening, and grid. 3dbox can also be used to represent other rectangular objects. Additional non-graphical attributes can be stored in Access database. Attributes can also be extracted to Excel and statistical analysis can be performed. All these can be done by programming in VBA which is found as a component in AutoCAD and many Microsoft Office applications including Access and Excel. Figure 7.2 shows the implementation environment and approach for the application tool.

![Figure 7.2 Implementation environment and approach](image)

**7.2.3 Design and Implementation of a Prototype**

Functional design of the system includes the design of Graphical User Interface (GUI), the design of tables in the Access database, linking graphical objects with the Access database, and data output to Excel for statistical analysis.
For the design of graphical user interface (GUI), Forms of VBA and the following controls have been used: Multipage control, Option button, Checkbox, Label, Textbox, RichTextbox, Command button etc. The Multipage control has been used for main functions of the application tool, such as Generate Structure, Input Drawing, Link to Excel, View Deviation, etc. In each main function, other controls, such as Option button, Checkbox, Label, Textbox, Command button, have been exploited for sub-functions. Figure 7.3 shows the user interface of function Generate Structure. Figure 7.4 and Figure 7.5 shows respectively the user interface of function View Deviation and Output.

Figure 7.3 The User Interface: Generate Structure

In Figure 7.4, apart from other controls, Frame control has also been used to group different kinds of deviations. In Figure 7.5, CommonDialogBox control has been exploited for file operation, and RichTextBox for displaying the texts.
The graphical objects in AutoCAD drawings have been linked with the tables in Access database by Data Access Objects (DAO) from VBA. Also, AutoCAD’s database connectivity feature can be used for this purpose. Database links within an AutoCAD drawing are simply pointers to a database table that references data from one or more records in that table.

Random number generator (normal distribution)
Most programming languages incorporate routines for sampling a random number between 0 and 1, which is also the case in VBA. An approximate sample from a univariate standardized normal distribution can be obtained from the formula:

\[ \varepsilon = \sum_{i=1}^{12} R_i - 6 \]  \hspace{1cm} (7-1)

where the \( R_i \) are independent random numbers between 0 and 1 \( (1 \leq i \leq 12) \) and \( \varepsilon \) is the required sample from \( \phi(0,1) \). This approximation can be used to generate

\( \phi \) denotes the cumulative distribution function (CDF) of the standard normal variable.
variables of standard normal distribution with mean 0 and standard deviation 1, and it is satisfactory for most purposes.

If a set of observations \( \{x_1, x_2, \ldots, x_n\} \) are obtained for a particular random variable \( X \), then the true mean \( \mu_X \) can be approximated by the sample mean \( \bar{x} \) and true standard deviation \( \sigma_X \) can be approximated by the sample standard deviation \( s_X \). Also probability paper can be used to obtain \( \mu_X \) and \( \sigma_X \).

\[
\bar{x} = \frac{1}{n} \sum_{i=1}^{n} x_i \tag{7-2}
\]

\[
s_X = \sqrt{\frac{\sum_{i=1}^{n} (x_i - \bar{x})^2}{n-1}} \tag{7-3}
\]

To generate a normally distributed random variable \( X \) with mean \( \mu_X \) and standard deviation \( \sigma_X \), the following formula is used:

\[
X = \mu_X + \epsilon \sigma_X \tag{7-4}
\]

In the implementation, the above-mentioned method has been used for generating random numbers of deviations that are distributed according to the normal distribution \( N(0, \sigma_X) \). The range of each deviation variable can be determined according to standards (NEN series 14), and \( \sigma_X \) can be approximated from samples.
In the implementation, in addition to the forms, there are also some modules to achieve certain functions such as Draw, Calculate etc., and they can also be called by the program for the forms.

**7.2.4 Running Prototype**

When running the prototype, it can generate typical structural assembly or read an IFC format drawing. Figure 7.6 shows a simplified floor plan in IFC format and it has been used as an input for the prototype.
Figure 7.6 A simplified floor plan in IFC format

Figure 7.7 shows that the tool marks positioning points on an element when the user selects the element. For each possible positioning point of an element, 100 random numbers of normal distribution have been generated. Figure 7.8 shows the generated numbers in the Access database. Figure 7.9 gives the X, Y, Z coordinates of the marked positioning points. Figure 7.10 and 7.11 depicts respectively the distribution of the predicted deviation limits of 2 positioning points, which is approximately the normal distribution.
Figure 7.7 Marking positioning points on an element

Figure 7.8 Generated random numbers of normal distribution in Access database
Figure 7.9 The X, Y, Z coordinates of marked positioning points of an element

Figure 7.10 Distribution of predicted deviation limits of Positioning Point 1
CONCLUDING REMARKS

This chapter has presented the idea of designing a computer aided dimensional control system (DCS). The implementation of a prototype of the DCS provides a digital way to bridge the floor plan design with dimensional control, predict dimensional deviation limits and output the data needed for a Total Station.

The DCS has used AutoCAD 3D objects to model the building structural elements. It can also read and use IFC based building models. However, in the building industry, AutoCAD 2D drawings are still widely used. With the development of IFC standards in the building industry, IFC based building modelling systems will replace current 2D drawing systems, which makes the DC system future proof.
CASE STUDY

*This chapter describes a case study in which the model and prototype have been applied into practice. The data has been collected on the construction site and analysed in house. Then the conclusion has been made based on the data analysis.*

8.1 OBJECTIVE

The purpose of doing this case study is to test the model and prototype, and show the proof of concept. This can be done by using the prototype tool in practice to position several building elements and comparing with the traditional way in the aspect of position accuracy.

8.2 CASE DESCRIPTION

The office-building project “La Tour” concerns an office building with 21 floor levels. Around this building a parking garage of 3 levels will be constructed. The construction of this building will be going on as follows: foundation of prefabricated piles, cellar, in-situ casting concrete core by way of climbing formwork, prefabricated inner wall plates, floor slabs, and further façade elements which will be prepared as much as possible on the construction site.
The project gets a local coordinate system in combination with the given municipal points from Apeldoorn. It should be noted that the municipal points are within R. D. system in Netherlands and have a scale factor, but the local coordinate system for construction doesn’t have a scale factor.

The local coordinate system is fixed outside the building area. It is fixed outside because the following reasons. First it reduces the risk of deformation of fixed points because once the points are fixed outside, fewer happenings will occur outside. Second it follows the rule of working from large to small area. Third there is more space outside than inside the building area and it gives foremen more play space.

When fixing the points (usually minimal 3) of local coordinate system, points should be fixed randomly and X, Y, and Z coordinates of each point should be measured using the municipal points as the base. This can be done by putting reflecting stickers on the existing objects and nails on the road outside around the building area.

From the outside points, then it is moving inside the building area until the foundation is poured. Then the MOUS system phase has arrived. The MOUS System consists of a set of specially designed materials, tools, instruments and procedures that can be used to establish main control points in buildings. The characteristics of the system is the way in which the main control points are marked – a piece of metal fixed to the floor with a specific inner diameter. Through openings in the construction, these pieces of pipe are aligned according to a vertical reference line and then fixed firmly to a part of the structure. The application of the system starts on the lowest concrete floor; main control points are set out and marked in the traditional way with a pencil, or set to the position with a Total Station. Over these pencil lines, a marker plate, a steel plate with a piece of pipe on it, is centred. Then the marker plate is fixed to the floor with mortar. Later on this MOUS point will be used as a reference for the local setting out process and once the upper floors are ready, for transferring MOUS points to these floors. The number of MOUS points on each floor depends on the number of
pours of floors and sequence of pouring. Usually minimal 2 points are needed for each pouring of the floor.

Figure 8.1 is the floor plan of the third level, Figure 8.2 is the section view of the building, and Figure 8.3 shows some pictures of the building project under construction.
8.3 COMPARISON OF THE MODEL WITH PRACTICE

The UML model and prototype developed in previous chapters are project independent and represents a more theoretical view of the dimensional control knowledge. In the model, the way to direct set out points using Total Station from a known point has been presented. Also, the building elements are viewed as columns, beams, floor slabs, walls and facades, which are objects instead of plain lines. In building construction practice, people use gridlines, offset method, MOUS systems and help devices etc. for setting out and positioning. This has been learned from interviewing the experts and visiting construction sites. Also, in practice, people still use plain AutoCAD drawings that consist of points, lines and arcs. This can be seen from the two figures above. This shows that people don’t think object oriented nor 3D yet.

In fact, the advantage of a Total Station is direct setting out points using coordinates or angle plus distance. This, in principle, improves accuracy because it reduces some unnecessary intermediate steps. Also the use of 3D building objects has more advantage than plain 2D drawings. This is because 3D objects are more
meaningful, easy to use and visualize. It should be noted that construction surveying and dimensional control is more advanced than other fields in construction. Construction surveying is already capable of working with 3D objects and other fields in construction need to catch up in this aspect.

8.4 PRACTICAL KNOWLEDGE
This section discusses some practical knowledge.
Horizontally, starting from 2 municipal points, main control points are set out outside the building area. These main control points can be used as a reference to check whether the building itself has absolute movement. This is because the main control points are fixed outside and are not moving along when the building moves. Also from these main control points, the MOUS points can be set out on the ground floor of the building. The number of MOUS points depends on the number of pours of floor and sequence of pouring. Usually for every pour, minimum two points are needed and an additional point is recommended for check. The location of the MOUS points has relationship with the gridline, usually a fixed offset of 0.5m or 1m.

The MOUS points can be used as the reference for later setting out of other positioning marks or intermediate points. From MOUS points, surveyors can set out directly the positioning marks for positioning objects using Total Stations. Some intermediate points can also be set out, upon which other site personnel than surveyors can work with and set out positioning marks using offset methods. The first approach delivers higher accuracy in principle, but demands high quality of people because only surveyors can do the work. The second alternative saves work and time, because once the intermediate points are set out, the surveyor doesn’t need to come back and set out again.

When people position building elements on construction sites, 75% use forced positioning and 25% use free positioning. And this is based on the assumption that the element itself is in theoretical dimensions. The method of forced positioning delivers higher accuracy because once the help device is positioned, the positioning crew can just put the building element against it. This way however perhaps takes more time and it requires additional help devices. The alternative of
free positioning can’t assure the required accuracy because the positioning crew can’t assure that the building element is positioned according to the marks set out on the floor.

In building construction, only the surveyors know the absolute level of points and people talk about the relative level of points for each floor. For the absolute level, the absolute construction level is based on the absolute country level that is NAP. Vertically, first, level 0 is defined and marked somewhere on the floor, usually a good safe position, preferably a MOUS point or a bolt; Then 1m plus level is created from the floor. Then the MOUS points can be transferred to upper floors by putting measuring tape through the holes of MOUS points or using other surveying equipment like a levelling instrument. Therefore for each floor, the same process repeats itself, that is, first level 0, then 1m plus.

To conclude, you can get the x and y coordinates of points on the floor by referring to the x and y coordinates of MOUS points, and z coordinate by referring to the top of MOUS points or bolts.

8.5 TEST
For this particular project of La Tour, the prototype developed before has been tested and improved. It functions as follows:

The GUI can read AutoCAD drawings of the floor plan and give advices on setting out the core construction horizontally and vertically by asking the user questions. The GUI first defines own coordinate system called RCS. This is because each drawing can have its own coordinate system and everything should be brought back to the same coordinate system. Then the GUI asks the user how many pours of floor there are and the sequence of pouring, and then it gives the number of MOUS points. The location of the MOUS point has relationship with the gridline, usually a fixed offset. Knowing the locations of the points, the system can add them into the floor plan. For vertical setting out, the MOUS points will be transferred upwards. The GUI asks the user to check for obstacles in the space with a range of 150mm. If obstacles are found, change the offset for everywhere and keep a safe offset; and also be careful with the distortion of signal/light. In the drawing of every floor, MOUS points have the same X, Y coordinate.
Steps:
1) Input drawing (third level floor plan, .dwg) completely or partially and then create IFC format objects.
2) Define own coordinate system RCS by asking two points from the drawing and then providing two new coordinates for them.
3) GUI asks questions:

<table>
<thead>
<tr>
<th>Question</th>
<th>Horizontal setting out</th>
<th>Vertical setting out</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pours of floor</td>
<td>Number of MOUS points</td>
<td>Obstacles in the space</td>
</tr>
<tr>
<td>Offset distance</td>
<td>Position of MOUS points</td>
<td>No obstacles in the space</td>
</tr>
</tbody>
</table>

8.6 MEASURING ON THE CONSTRUCTION SITE

The following steps have been carried out on the construction site of La Tour in Apeldoorn to measure and collect data.

1) Select two columns as study objects, one sloped and the other vertical. The locations of the two columns have theoretical relationships with the position of MOUS points (X, Y), and the line of 1m plus for the height (Z). The Total Station must be set up in a location where the MOUS points, 1m plus line and two columns can be easily seen. Figure 8.4 shows the foundation plan including the sloped column numbered as 212 and the vertical one 216. See Figure 8.5 for the location of the Total Station and the vertical column on the site, and Figure 8.6 for the location of the sloped column on the site.

2) Put the reflecting stickers on two columns. On the sloped column, choose one side surface and find the practical centre line of it. The width of the surface is 60cm as measured, therefore the centre line is 30cm from both edges. Then find another two points each having a distance of 10cm from the edge, that is to say, 10cm and 50cm. For the height, use the line of 1m plus on the column as the basis. From this line, create the line of 3.5m and
6.0m respectively. Put the reflecting sticker respectively on these nine points. The process of this step should repeat for the vertical column, but only 6 points on one side surface of it are chosen, because of the non-accessibility of the top 3 points. See Figure 8.5, 8.6 and 8.7.

3) Put the reflecting aiming device on the two MOUS points and the reflecting sticker on the line of 1m plus. See Figure 8.8, 8.9 and 8.10.

4) Set up the tripod and the Total Station using Free Station method. Comparing Free Station with Fixed Station, the former skips out centring error and gives a better sight. The tripod legs must be firmly pressed into the ground so that no movement can occur in the instrument as the surveyor moves round or when traffic moves nearby, and the wing nuts clamping the legs must be tight. The Total Station must be levelled according to the following procedure. Rotate the inner axis so that the bubble tube is parallel to two of the foot screws. Turning those foot screws, the bubble is brought to the centre of its run. The foot screws are turned simultaneously with the thumbs moving towards each other or away from each other. The left thumb movement gives the direction of the consequent movement of the bubble. Check the bubble by turning half round (180°) and the bubble movement should be within half of the unit of the hairline. This step is an internal check of the bubble to ensure it is all right. Rotate the inner axis so that the bubble tube is at right angles to its former position, when it should be parallel to a line joining the third foot screw to the mid-point of the line joining the other two. Bring the bubble to the centre of its run using the third screw only. A correctly adjusted instrument will now be levelled, and as the horizontal circle rotates and takes the bubble tube round, then the bubble should remain at the centre of its run everywhere. See Figure 8.5 and 8.11.

5) Choose “Free Station” in the software of the Total Station. The Total Station asks for the first aiming position number; if the number is not known in its memory, the point information including number, X, Y and Z needs to be input by the surveyor; sight at the first position (MOUS point 1) and record horizontal plus vertical angle and slope distance. This is the first reading. Repeat the process for the second position (MOUS point 2) and
record the reading. Use the “Calculation” function of Total Station and calculate the deviation between theoretical distance of two positions and practical distance. It is acceptable when the deviation is below 2mm. Otherwise, the surveyor should repeat the above process. After knowing the system deviation is within 2mm, proceed and use the Total Station to calculate the X, Y, and Z coordinates of its own position and the horizontal origin. Sight the line of 1m plus and record the reading.

6) Sight the reflecting stickers on the sloped column and the vertical one, and measuring the X, Y, Z coordinate of each point. When sighting the reflecting sticker, usually aim at the middle. However, for the top 3 points of the sloped column, aim at the top line of the sticker, because the top position of the column is known.

8.7 ANALYZING THE DATA

The final position deviation of an object comes from the deviation of surveying instrument, the deviation of setting out marks including main control points and positioning marks for the object, positioning deviation, and the product deviation of the object. In this case study, the surveying instrument is the Total Station that has a deviation of 2mm in distance measurement and 0.0006g in angle measurement; the main control points are two MOUS points having a deviation of 2mm position; the positioning deviation of objects includes 3 translation and 3 rotation in the 3D space; and the product deviation includes deviation in 1D, 2D and 3D.

8.7.1 The Vertical Column

Figure 8.12 shows the vertical column with numbered points on one side surface. Table 8.1 lists the data collected on the construction site as well as theoretical data obtained from the drawing.
Figure 8.4 The two study columns in the foundation plan

Figure 8.5 Location of the Total Station and the vertical column on the site
Figure 8.6 The sloped column on the site

Figure 8.7 Zooming in of the 3 stickers (middle, left and right) on the sloped column

Figure 8.8 Putting the reflecting aiming device on one MOUS point on the site
Figure 8.9 Putting the reflecting aiming device on the other MOUS point on the site

Figure 8.10 Putting reflecting stickers on the level of 1m plus

Figure 8.11 Setting up the Tripod and Total Station using Free Station
Table 8.1 Data about points on the side surface of vertical column

<table>
<thead>
<tr>
<th>Point No.</th>
<th>Measured Data (m)</th>
<th>Theoretical Data (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X</td>
<td>Y</td>
</tr>
<tr>
<td>2010</td>
<td>115.297</td>
<td>1000.991</td>
</tr>
<tr>
<td>2011</td>
<td>115.495</td>
<td>1000.992</td>
</tr>
<tr>
<td>2012</td>
<td>115.695</td>
<td>1000.995</td>
</tr>
<tr>
<td>2013</td>
<td>115.296</td>
<td>1000.995</td>
</tr>
<tr>
<td>2014</td>
<td>115.496</td>
<td>1000.998</td>
</tr>
<tr>
<td>2015</td>
<td>115.696</td>
<td>1001.000</td>
</tr>
</tbody>
</table>

1) Check the rotation of points around Z-axis on the line of 1m plus and the line of 3.43m plus.
   1.1) Check the Y coordinates of point 2010, 2011 and 2012, compare them with the theoretical Y coordinates 1001.000.
   1.2) Check the Y coordinates of point 2013, 2014 and 2015, compare them with the theoretical Y coordinates 1001.000.
   1.3) Draw Figure 8.13.
Figure 8.13 Rotation of points around Z-axis on the line of 1m plus and the line of 3.43m plus.

Figure 8.13 shows that the column not only rotates around Z-axis, but also has a translation along Y direction. It also shows that the column has a rotation around X-axis. At the level of 1m plus, the rotation around Z-axis is 4mm in 400mm, which equals to 0.57°. Due to the 2mm deviation from Total Station, it can only be said that the rotation is in the range of 2mm to 6mm, which means 0.29° to 0.86°. Also at this level, it can be concluded that there is a 5mm translation along Y direction. At the level of 3.43m plus, the rotation around Z-axis is 5mm in 400mm, which equals to 0.72°. Considering the 2mm deviation from Total Station, it can only be said that the rotation is in the range of 3mm to 7mm, which means 0.43° to 1.00°.

2) Check the translation in X direction.
2.1) Calculate the average of X coordinates of point 2010 and 2012, compare this average value with the X coordinate of point 2011. This is an internal check of object itself, which shows the product deviation in width (X direction, at the height of 1m plus) of the column.
\[ X_{2011\text{Ave}} = (115.297 + 115.695)/2 = 115.496 \]

You can see from the table that the practical X coordinate of point 2011 is 115.495. Therefore it shows that the product deviation in width is 1mm. Considering the fact that the distance measuring deviation of the Total Station is 2mm, the product deviation in width is within the specification of the factory.

Now define the average of \( X_{2011\text{Ave}} \) and practical \( X_{2011} \) as \( X_{2011\text{Abs}} \) and it is 115.4955.

2.2) Calculate the average of X coordinates of point 2013 and 2015, compare this average value with the X coordinate of point 2014. This is an internal check of object itself, which shows the product deviation in width (X direction, at the height of 3.42m plus) of the column.

\[ X_{2014\text{Ave}} = (115.296 + 115.696)/2 = 115.496 \]

You can see from the table that the practical X coordinate of point 2014 is 115.496. Therefore it shows that the product deviation in width is 0mm.

Now define the average of \( X_{2014\text{Ave}} \) and practical \( X_{2014} \) as \( X_{2014\text{Abs}} \) and it is 115.496.

2.3) Compare \( X_{2011\text{Abs}} \) with \( X_{2014\text{Abs}} \), you get the translation of 0.0005mm in X-axis, which can be neglected.

3) Check the rotation around X-axis and Y-axis respectively.

3.1) Check the rotation around X-axis by comparing three pairs of Y coordinates:
- \( Y_{2010}, Y_{2013} \) derive the rotation in left (4mm)
- \( Y_{2011}, Y_{2014} \) derive the rotation in centre (6mm)
- \( Y_{2012}, Y_{2015} \) derive the rotation in right (5mm)

The average of above three values is 5mm, therefore the difference in left, centre and right is respectively –1mm, 1mm, and 0mm. These values are all within the specification of Total Station (2mm). And you get a rotation of 5mm in 2.430m around X-axis, that is to say, the rotation angle is 0.1°. Considering the 2mm deviation from Total Station, it can only be said that the rotation is in the range of 3mm to 7mm, which means 0.07° to 0.16°.

3.2) Check the rotation around Y-axis by comparing three pairs of X coordinates:
- \( X_{2010}, X_{2013} \) derive the rotation in left (-1mm)
X_{2011}, X_{2014} \quad \text{derive the rotation in centre (-1mm)}
X_{2012}, X_{2015} \quad \text{derive the rotation in right (-1mm)}

The average of above three values is \(-1\)mm, therefore the difference in left, centre and right is all 0mm and it is within the specification of Total Station. There is no rotation around Y-axis.

4) Check the translation in Z direction.
Considering the fact that:
\[
\frac{(Z_{2010} + Z_{2011} + Z_{2012})}{3} = 1.002\text{m}
\]
the theoretical Z is 1.000m
you get a deviation of 2mm.
For the height of 3.43m:
\[
\frac{(Z_{2013} + Z_{2014} + Z_{2015})}{3} = 3.431\text{m}
\]
But no theoretical reference is available, therefore no conclusion can be drawn.

To summarize above 4 steps, it can be concluded that the column rotates around Z-axis and X-axis, translates in X, Y and Z direction. See the following for details.
Rotation around Z-axis:
at 1m plus level: in the range of 0.29° to 0.86°
at 3.43m plus level: in the range of 0.43° to 1.00°
Rotation around X-axis: in the range of 0.07° to 0.16°
Translation in X direction: 0.0005mm
Translation in Y direction: 5mm (at 1m plus level)
Translation in Z direction: 2mm (at 1m level)

8.7.2 The Sloped Column
Figure 8.14 shows the sloped column with numbered points on one side surface.
Table 8.2 lists the data collected on the construction site, the theoretical data derived from the drawing, as well as the theoretical data obtained from calculation (see calculation at 3.1 on page 120).
Figure 8.14 The sloped column with numbered points on one side surface

Table 8.2 Data about points on the side surface of sloped column

<table>
<thead>
<tr>
<th>Point No.</th>
<th>Measurement Data (m)</th>
<th>Theoretical Data (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X</td>
<td>Y</td>
</tr>
<tr>
<td>2001</td>
<td>136.595</td>
<td>1004.697</td>
</tr>
<tr>
<td>2002</td>
<td>136.595</td>
<td>1004.493</td>
</tr>
<tr>
<td>2003</td>
<td>136.597</td>
<td>1004.294</td>
</tr>
<tr>
<td>2004</td>
<td>136.598</td>
<td>1004.495</td>
</tr>
<tr>
<td>2005</td>
<td>136.599</td>
<td>1004.293</td>
</tr>
<tr>
<td>2006</td>
<td>136.598</td>
<td>1004.096</td>
</tr>
<tr>
<td>2007</td>
<td>136.596</td>
<td>1004.282</td>
</tr>
<tr>
<td>2008</td>
<td>136.598</td>
<td>1004.085</td>
</tr>
<tr>
<td>2009</td>
<td>136.596</td>
<td>1003.886</td>
</tr>
</tbody>
</table>

1) Check all X coordinates of the nine points and compare them with the theoretical X coordinates and draw Figure 8.15.

Figure 8.15 shows that the column not only rotates around Z-axis, but also has a translation along X direction. It also shows that the column has a rotation around Y-axis. At the level of 1.004m plus, the rotation around Z-axis is 2mm in 402mm,
which equals to 0.3°. Due to the 2mm deviation from Total Station, it can only be said that the rotation is in the range of 0mm to 4mm, which means 0° to 0.6°. Also at this level, it can be concluded that there is a 3mm translation along X direction. At the level of 3.485m plus, the rotation around Z-axis is 1mm in 402mm, which equals to 0.1°. Considering the 2mm deviation from Total Station, you can say that there is no rotation around Z-axis at this level. At the level of 6.137m plus, the rotation around Z-axis is 2mm in 402mm, which equals to 0.3°. Also there is 2mm translation in X direction. Considering the 2mm deviation from Total Station, you can say that the rotation is in the range of 0 to 0.6°, and the translation in X direction is between 0 to 4mm.

2) Check the translation in Z direction
Considering the fact that:
\((Z_{2001} + Z_{2002} + Z_{2003}) / 3 =1.004\text{m}\)
\((Z_{2004} + Z_{2005} + Z_{2006}) / 3 =3.485\text{m}\)
\((Z_{2007} + Z_{2008} + Z_{2009}) / 3 =6.135\text{m}\)
You get a deviation of 4mm at the level of 1m. Considering the specification of Total Station, the translation is between 2mm and 6mm. For the level of 3.485m and 6.137m, there are no theoretical data available, thus no conclusion can be drawn for the translation at these two heights.

3) Check the Y coordinates of all three levels.
3.1) Calculation of the theoretical coordinates
The calculation is done according to the following formula:
\(Y_{\text{side-final}} = Y_{\text{base}} - \text{height*height\_ratio} - Y_{\text{measurement\_shift}}\)

\(Y_{2001} = 1004.900 - (1.004 + 0.300)\times 273/3400 - 0.100 = 1004.695\)
\(Y_{2002} = (1004.900 + 1004.298)/2 - (1.003 + 0.300)\times 273/3400 = 1004.494\)
\(Y_{2003} = 1004.298 - (1.004 + 0.300)\times 273/3400 + 0.100 = 1004.293\)
\(Y_{2004} = 1004.900 - (3.5 + 0.300)\times 273/3400 - 0.100 = 1004.495\)
\(Y_{2005} = (1004.900 + 1004.298)/2 - (3.485 + 0.300)\times 273/3400 = 1004.295\)
\(Y_{2006} = 1004.298 - (3.471 + 0.300)\times 273/3400 + 0.100 = 1004.095\)
\(Y_{2007} = 1004.900 - (6.151 + 0.300)\times 273/3400 - 0.100 = 1004.282\)
Figure 8.15 Rotation around Z-axis

\[
Y_{2008} = \frac{(1004.900 + 1004.298)}{2} - (6.137 + 0.300) \times \frac{273}{3400} = 1004.082
\]

\[
Y_{2009} = 1004.298 - (6.117 + 0.300) \times \frac{273}{3400} + 0.100 = 1003.883
\]

3.2) Calculate the average of Y coordinates of point 2001 and 2003, compare this average value with the Y coordinate of point 2002. This is an internal check of object itself, which shows the product deviation in width (Y direction, at the height of 1.004m plus) of the column.

\[
Y_{2002Ave} = \frac{(1004.697 + 1004.294)}{2} = 1004.4955
\]

You can see from the table that the practical Y coordinate of point 2011 is 1004.493. Therefore it shows that the product deviation in width is 2.5mm. Considering the fact that the distance measuring deviation of the Total Station is 2mm, the product deviation in width is in the range of 0.5mm and 4.5mm.

Now define the average of \(Y_{2002Ave}\) and practical \(Y_{2002}\) as \(Y_{2002Abs}\) and it is 1004.4943.

3.3) Calculate the average of Y coordinates of point 2004 and 2006, compare this average value with the Y coordinate of point 2005. This is an internal check of object itself, which shows the product deviation in width (Y direction, at the height of 3.485m plus) of the column.
\[ Y_{2005\text{Ave}} = \frac{(1004.495+1004.096)}{2} = 1004.2955 \]

You can see from the table that the practical Y coordinate of point 2005 is 1004.293. Therefore it shows that the product deviation in width is 2.5mm. Considering the fact that the distance measuring deviation of the Total Station is 2mm, the product deviation in width is in the range of 0.5mm and 4.5mm.

Now define the average of Y\text{2005Ave} and practical Y\text{2005} as Y\text{2005Abs} and it is 1004.2943.

3.4) Calculate the average of Y coordinates of point 2007 and 2009, compare this average value with the Y coordinate of point 2008. This is an internal check of object itself, which shows the product deviation in width (Y direction, at the height of 6.137m plus) of the column.

\[ Y_{2008\text{Ave}} = \frac{(1004.282+1003.886)}{2} = 1004.084 \]

You can see from the table that the practical Y coordinate of point 2008 is 1004.085. Therefore it shows that the product deviation in width is 1mm. Considering the fact that the distance measuring deviation of the Total Station is 2mm, the product deviation in width is within the specification of the factory.

Now define the average of Y\text{2008Ave} and practical Y\text{2008} as Y\text{2008Abs} and it is 1004.0845.

The translation in Y is 2mm, and it also shows a rotation around X at 1mm in 2.57m that can be neglected.

4) Check the rotation around X-axis by comparing three sets of Y coordinates:

- Y\text{2001}, Y\text{2004}, Y\text{2007} derive the rotation in left (2mm)
- Y\text{2002}, Y\text{2005}, Y\text{2008} derive the rotation in centre (2mm) and translation in Y (2mm)
- Y\text{2003}, Y\text{2006}, Y\text{2009} derive the rotation in right (2mm) and translation in Y (1mm)

The rotation around X-axis is 2mm in 5.133m and the translation in Y is 2mm. Considering the 2mm deviation from Total Station, it can only be said that the rotation around X-axis is in the range of 0mm to 4mm, which means 0 to 0.04°.
5) Check the rotation around Y-axis by comparing three sets of X coordinates:

$X_{2001}, X_{2004}, Y_{2007}$ → derive the rotation in left (2mm) and translation in X (3mm)

$X_{2002}, X_{2005}, Y_{2008}$ → derive the rotation in centre (3mm) and translation in X (2mm)

$X_{2003}, X_{2006}, Y_{2009}$ → derive the rotation in right (1mm) and translation in X (3mm)

The rotation around Y-axis is 2mm in 5.133m and the translation in X is 2.67mm. Considering the 2mm deviation from Total Station, it can only be said that the rotation around Y-axis is in the range of 0 to 4mm, which means 0 to 0.04°. And the translation in X is in the range of 0.67mm to 4.67mm.

To summarize above steps, it can be concluded that the column rotates around Z-, Y- and X-axis, translates in X, Y and Z direction. See the following for details.

Rotation around Z-axis:
- at 1.004m plus level: in the range of 0° to 0.6°
- at 3.485m plus level: no rotation
- at 6.137m plus level: in the range of 0° to 0.6°

Rotation around X-axis: in the range of 0° to 0.04°

Rotation around Y-axis: in the range of 0° to 0.04°

Translation in X direction: in the range of 0.67mm to 4.67mm

Translation in Y direction: 2mm

Translation in Z direction: in the range of 2mm to 6mm (at 1m level)

8.8 CONCLUSIONS

The DCS has been applied in the case study by using AutoCAD drawing, Total Station plus storing device and stickers, whereas the traditional technique is paper, theodolite plus notes and measuring tape. Comparing the case method with the traditional technique, you get a list of advantages and disadvantages as follows.

Advantages of the DCS method over traditional technique:
- Speed is higher because there is no intermediate points
- Accuracy is higher because there is no intermediate points
- Reliability is higher because it reduces the chances of human mistakes by inputting data directly from computer to Total Station instead of paper notes
- Low cost for the overall method
- It can work in 3D where traditional methods cannot
- It works very well with (pre)positioning of free form object in 3D
- Temperature independent
- It can reach NEN very easily

Disadvantages of the DCS method:
- Expensive as a start. Total Station costs NLG 18000
- People with higher quality of knowledge required

Weighing the advantages over disadvantages, the following conclusions on the DCS method can be drawn:
- Higher accuracy
- Less time consuming (around 50%)
- Highly profitable
- Can be used on all construction works

Therefore the case study shows that the method presented in the model and prototype of the DCS has big benefit for the construction companies if applied appropriately.
CONCLUSIONS AND RECOMMENDATIONS

This chapter summarizes the conclusions of the research and formulates some recommendations for further study.

9.1 RECAPITULATING THE PROBLEM

The increased use of prefabricated components, the complexity of new building shapes, and the speeding up of production in construction, demand an efficient and precise dimensional control. Meanwhile Information and Communication Technology (ICT) increasingly supports construction, among others, CAD systems and Total Stations, are being used for the purpose of dimensional control.

In order to improve the dimensional control of on-site construction projects, this research tries to capture the knowledge required to design an adequate dimensional control plan and make that knowledge more generally available, and build a connection between CAD systems and Total Stations by applying state-of-art ICT, focusing on prefabricated concrete building structural elements.
9.2 CONCLUSIONS

This thesis presents a method for estimating dimensional deviations and an information model that defines the various deviations and represents engineering experience knowledge using UML. The model has been implemented in a Dimensional Control System (DCS) and applied in the “La Tour” construction project in Apeldoorn, the Netherlands.

The conclusions of this research have been summarized as follows:

1) The proposed simulation method and UML information model show a way to handle the dimensional deviations and structure the dimensional control knowledge in a computer interpretable manner.

2) The implementation of a prototype of the DCS provides a digital way to bridge the floor plan design with dimensional control, predict dimensional deviation limits and output the data needed for a Total Station.

3) The case study tests the UML model and prototype of the DCS. The results prove that direct positioning of objects (by putting reflectors on the objects and using a Total Station and by inputting coordinates extracted and calculated from the AutoCAD drawings) provides higher speed, accuracy and reliability. It also shows a way to (pre)position a free form object in 3D where traditional methods cannot. This means that fulfilling the clients’ desire to increased freedom in shapes can be supported by the DCS.

4) With the development of IFC standards in the building industry, IFC based building modelling systems will replace current 2D drawing systems, which makes the DC system future proof.

5) Applying the DCS in the building industry needs a consistent ICT infrastructure in different phases of building design and construction. The contract form of Design & Construct stands out as a good way of working to facilitate the consistency and to provide a knowledge learning and management environment. Also, there is a trend towards performance contracts. Dimensional quality is a performance. Performance specifications are only useful if it is possible to control the performance, which requires a
DCS that can predict and measure the dimensional quality. Therefore, in turn, the DCS will contribute to the improvement of building process.

To conclude, from the scientific point of view, this research is a first step towards providing dimensional quality in a construction process covered by stochastic dimensional uncertainty, even for positioning of free form objects. The application of the DCS will contribute to increased confidence in dimensional control and the reduction of costs of failure, which potentially could support the increased use of cheaper construction methods, and will also contribute to the improvement of building design and construction process.

9.3 RECOMMENDATIONS

This research has produced results from an effort to develop an intelligent system for designing dimensional control plans. These results have been shown in the conclusion. Based on this research experience, some recommendations can also be given as follows:

1) Increase the knowledge contents of the DCS and perform more research on the application of Knowledge Technology (KT) in the field of dimensional control

Using the DCS in practice might result in situations where the system fails and the implementation of additional knowledge rules can be helpful. Therefore it is recommended to elicit more knowledge from practice and add it to the DCS. Also more research should be done on the application of KT in the field of dimensional control, which includes Fuzzy logic and inductive knowledge such as Neural Networks, Genetic Algorithm and Case Based reasoning.

2) Develop the DCS into a commercial product with added features

The DCS is not as user friendly as it could be in regard to presenting the information. In presenting information, Virtual Reality (VR) is more attractive than current 3D graphics. VR allows the user to see the virtual construction site including the components at hand and their positioning points plus the Total Station on the scene. This will present the user with better insight in the
positioning problems, which might be quite beneficial especially in complex measurement situations. In further development, VR functionality should be added.

To conclude, it is worthwhile to develop the current DCS into a commercial product with added features.

3) Develop a national or international CAD layering convention extension for dimensional control

As mentioned above, the DCS is not as user friendly as it could be, which is also true in inputting or extracting the design data. The DCS has used AutoCAD 3D objects to model the building structural elements. It can also read and use IFC based building models. However, in the building industry, AutoCAD 2D drawings are still widely used. This raises an issue to develop a national or international CAD layering convention extension for dimensional control, because currently it seems that each company has its own CAD layer naming conventions. If there is a common layer naming convention extension that serves the purpose of dimensional control (i.e. a convention that can be added to existing layering conventions to produce the same input for the DCS), it is possible to write some macros and directly pick up the input data for the DCS directly from a traditional set of electronic AutoCAD drawings.

4) Create a long-term coalition among different parties in the building industry

The trend toward performance process contracts demands better cooperation among various parties in the building industry. The contract form of Design & Construct proves as a good collaboration way. Currently the collaboration is temporary because it is gone after the building project is finished. Therefore it is recommended that various parties can form a long-term coalition.
Appendix

The Unified Modelling Language (UML) is a language for specifying, visualizing, constructing, and documenting the artefacts of software systems, as well as for business modelling and other non-software systems. In terms of the views of a model, the UML defines the following graphical diagrams:

- use case diagram
- class diagram
- behaviour diagrams:
  - statechart diagram
  - activity diagram
- interaction diagrams:
  - sequence diagram
- collaboration diagram
- implementation diagrams:
  - component diagram
- deployment diagram

This part gives a simplified description of UML class diagram and its elements.
In this diagram, the graphical representation of Class and some relationships between classes are depicted.

Class

A class is a set of objects that share a common structure and common behaviour (the same attributes, operations, relationships and semantics). A class is an abstraction of real-world items. When these items exist in the real world, they are instances of the class and are referred to as objects.

A class icon is drawn as a 3-part box, with the class name in the top part, a list of attributes (with optional types and values) in the middle part, and a list of operations (with optional argument lists and return types) in the bottom part.

The attribute and operation sections of the class box can be suppressed to reduce detail in an overview. Suppressing a section makes no statement about the absence of attributes or operations, but drawing an empty section explicitly states that there are no elements in that part.

An object has state, behaviour, and identity. The structure and behaviour of similar objects are defined in their common class. Each object in a diagram indicates some instance of a class. An object that is not named is referred to as a class instance.

Relationships

You can draw the following relationships between classes:
Aggregate
Association
Generalize

In this appendix, the above-mentioned three kinds of relationships have been explained. For more on UML, the reader can refer to other books listed in the references.
Aggregation

Use the aggregate relationship to show a whole and part relationship between two classes.

The class at the client end of the aggregate relationship is sometimes called the aggregate class. An instance of the aggregate class is an aggregate object. The class at the supplier end of the aggregate relationship is the part whose instances are contained or owned by the aggregate object.

Use the aggregate relationship to show that the aggregate object is physically constructed from other objects or that it logically contains another object. The aggregate object has ownership of its parts.

By default, the aggregation tool on the toolbox is uni-directional and drawn on a diagram with a single arrow on one end of the aggregation and a diamond on the other end. A uni-directional aggregate only allows navigation to flow one way. The end with the arrow indicates who or what is receiving the action.

In the above graphic, a uni-directional aggregation with graphical representation of a diamond appears between class2 and class3. The diamond end designates the client class.

Generalize

A generalize relationship between classes shows that the subclass shares the structure or behaviour defined in one or more superclasses. Use a generalize relationship to show an "is-a" relationship between classes.

A generalize relationship is a solid line with an arrowhead pointing to the superclass.
Association

An association provides a pathway for communication. The communication can be between use cases and actors, between two classes or between a class and an interface. Associations are the most general of all relationships and consequentially the most semantically weak. If two objects are usually considered independently, the relationship is an association.

An association relationship is an orthogonal or straight solid line with an arrow at one end. By default, the association tool on the toolbox is uni-directional and drawn on a diagram with a single arrow at one end of the association. The end with the arrow indicates who or what is receiving the communication.
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Summary

Dimensional control in the building industry can be defined as the operational techniques and activities that are necessary, during the construction process of a building, for the assurance of the defined dimension quality of a building (Hoof, 1986). Efficient and precise dimensional control of buildings under construction is becoming ever more important because of changes in the construction industry. More prefabricated components are used; more regulations appear; newly designed buildings have more complex shapes, and building construction is speeding up.

To ensure the predefined dimensional quality, a plan of dimensional control must be designed, on the basis of building drawings and specifications delivered by architects, before the building is constructed. The dimensional control plan must provide site personnel with adequate information on, among others, setting out and assembling building components, which can often be done by means of Total Stations.

The essence of designing a dimensional control plan is to find out which points should be used as positioning points, which points should be set out in advance or controlled afterwards, and not to forget why.

In an effort to contribute to the improvement of the dimensional control of on-site construction projects, this research tries to capture the knowledge required to design an adequate dimensional control plan and make that knowledge more generally available, and build a digital connection between CAD systems and Total Stations, focusing on prefabricated concrete building structural elements.

The instrument developed in this research for capturing of essential dimensional control information and knowledge makes use of Product Data Technology (PDT) and Knowledge Technology (KT). The chosen solution supports the stochastic analysis of optimal positioning points taking account of various sorts of deviations and their mutual relationships.
The resulting information model has been written in a standardized information modelling language called UML (Unified Modelling Language).

The model has been implemented in a Dimensional Control System (DCS) and applied in the “La Tour” construction project in Apeldoorn, the Netherlands. The DCS provides a digital way to bridge the floor plan design with dimensional control, predict dimensional deviation limits and output the data needed for a Total Station. The case study of “La Tour” tests the UML model and prototype of the DCS.

The results prove that direct positioning of objects (by putting reflectors on the objects and using a Total Station and by inputting coordinates extracted and calculated from the AutoCAD drawings) provides higher speed, accuracy and reliability. It also shows a way to (pre)position free form objects in 3D where traditional methods cannot.

In conclusion:

(1) it seems to be justified to expect that the application of the DCS will contribute to increased confidence in dimensional control and the reduction of costs of failure, which potentially could support the increased use of cheaper construction methods, and will also contribute to the improvement of building design and construction process.

(2) the scientific contribution of this research is a first step towards providing dimensional quality in a construction process covered by stochastic dimensional uncertainty, even for positioning of free form objects.
Samenvatting


Om vooraf bepaalde maatkwaliteiten te garanderen moeten er, op basis van de door de architect aangeleverde ontwerptekeningen en bestek, maatbeheersingsplannen worden ontworpen. Een maatbeheersingsplan moet de werkers op de bouwplaats optimale informatie verschaffen met betrekking tot uitzetten en assembleren van bouwelementen. Bij het uitzetten en assembleren van bouwelementen wordt tegenwoordig vaak gebruik gemaakt van Total Stations.

De essentie van het ontwerpen van een maatbeheersingsplan is vast te stellen welke meetpunten als positioneringspunten gebruikt moeten worden en welke punten vooraf moeten worden uitgezet, of achteraf gecontroleerd, en (vooral ook) waarom.

In een poging om bij te dragen aan de maatbeheersing van bouwprojecten probeert dit onderzoek kennis die nodig is om een doelmatig maatbeheersingsplan te ontwerpen breed toegankelijk te maken door deze vast te leggen in een instrument, te weten een computergestuurd maatbeheersingssysteem. Ook wordt het mogelijk gemaakt electronisch gegevens uit te wisselen tussen CAD-systemen en Total Stations. Bij de verdere uitwerking ligt de nadruk op het uitzetten en assembleren van geprefabriceerde constructieve elementen.

Het in dit onderzoek ontwikkelde instrument maakt voor het vastleggen van de benodigde maatvoeringsinformatie en -kennis gebruik van Product Data Technologie (PDT) en Kennis Technologie (KT). De gekozen oplossing
ondersteunt de statistische berekening van de optimale positionereingspunten rekening houdend met een groot aantal mogelijke maatafwijkingen en hun onderlinge samenhang. Het resulterende informatiemodel is beschreven in de gestandaardiseerde, object georienteerde modelleringstaal UML (Unified Modelling Language). Het UML model is vervolgens geïmplementeerd en getest in het “La Tour” bouwproject in Apeldoorn. Uit veldtesten blijkt dat het ontwikkelde instrument beter scoort dan de bestaande methoden met betrekking tot snelheid, nauwkeurigheid en betrouwbaarheid, met name bij complexe positioneringsproblemen. Tevens wordt aangetoond dat het instrument instaat is om willekeurig gevormde objecten te positioneren, iets waar in de praktijk behoefte aan bestaat (speciaal bij geprefabriceerde betonelementen) en dat niet mogelijk is met de bestaande methoden.

Het realiseerde instrument biedt een digitale brug tussen vloerplanontwerp en maatbeheersing, voorspelt maximale maatafwijkingen en levert direct bruikbare invoer voor Total Stations.

De volgende conclusies lijken derhalve gerechtvaardigd:

(1) het ontwikkelde instrument zal bij kunnen dragen aan een toenemend vertrouwen in de beheersbaarheid van maatvoering in de Bouw en daarmee aan een afname van faalkosten, een toename van goedkopere bouwmethoden en aan het verbeteren van het ontwerp- en uitvoeringsproces.

(2) de wetenschappelijke bijdrage van dit onderzoek is een eerste stap in het bereiken van maatkwaliteit in bouwprocessen die worden beheerst door stochastische maatonzekerheid, ook in geval van vrij gevormde objecten.
Curriculum Vitae

Rui Wu (1971, China), completed high school study in 1988 and was enrolled at the Department of Electrical Engineering at Taiyuan University of Technology in the same year. In 1992 she graduated from the university with the degree of Bachelor of Engineering and with the award of Excellent Graduate. After working for half a year, she attended Wuhan Technical University of Surveying & Mapping for postgraduate study of Geographical Information System in 1993. Due to her excellent study results, she was recommended to continue her postgraduate study at International Institute for Aerospace Survey and Earth Sciences (ITC), the Netherlands, in the fall of 1994. She graduated from ITC in June 1996 with the degree of Master of Science and the award of distinction. She started her Ph.D research at Eindhoven University of Technology in September 1996.
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Stellingen
Behorende bij het proefschrift “Computer Aided Dimensional Control in Building Construction” door Rui Wu

1. As Monte-Carlo simulation is able to handle a large amount of stochastic variables, it is suited for predicting the dimensional deviation limits in building construction.  
   *This thesis.*

2. Direct positioning of objects using reflectors, Total Stations and the DCS (Dimensional Control System), provides higher speed, accuracy and reliability.  
   *This thesis.*

3. With the development of IFC standards in the building industry, IFC based building modelling systems will replace current 2D CAD drawing systems in the future.  
   *This thesis.*

4. The next generation, XML-based Internet will finally allow the construction industry to replace its paper based Information System (IS) by an electronic IS, as it will be safe, secure, fast, inexpensive and generally available.

5. If the current trend towards “intelligent documents” progresses, in the future traditional paper based construction documents will be replaced by intelligent electronic construction documents. At that time an intelligent dimensional control plan will know what it should achieve and be able to achieve it, i.e. dimensional accuracy.

6. The crash of once high-flying dot.coms shows that Internet technology can be best utilized for traditional industries, but not replace the latter as some had expected.
7. Looking at what is happening in the world around us, it might not be a bad idea to replace human intelligence by computer intelligence after all.

8. The people of a country and the government of a country are often considered as the same concept though in fact they are different.

9. The world is still divided, and it is more difficult to overcome the cultural barriers than to remove the country borders.

10. There will be no fish in extremely clean waters (Chinese saying).