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Rotterdam 10 juli 2008

Collapse of a tower crane

Rotterdam 10 july 2008

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THE DUTCH SAFETY BOARD

The Dutch Safety Board was created with the purpose of investigating and establishing the causes or probable causes of individual or categories of incidents in all sectors. The goal of such investigations is solely to prevent future accidents or incidents and, if the findings give reason for this, to provide relevant recommendations. The organisation consists of a board with five permanent members, a professional bureau and several permanent committees. Guidance committees are created for specific investigations.

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Please note:
This report is drawn up in Dutch, English and German. In the event of any differences in interpretation, the Dutch text shall prevail.

CONSIDERATIONS

The collapse of the tower crane in Rotterdam

This report from the Dutch Safety Board is the outcome of an investigation into the collapse of a tower crane at Prinsenlaan in Rotterdam on 10 July 2008. The tower crane was located near a block of high-rise flats and seemed to collapse for no apparent reason. The crane operator, who was situated 96 metres above ground in the crane, died in the accident. The falling crane caused extensive damage to the construction site. Potentially, the incident could have caused many more injuries or fatalities on the construction site, or on the nearby footpath or children's play area.

The circumstances surrounding the incident

The investigation has demonstrated that the collapse of the tower crane can be attributed to a series of shortcomings. The flexibility of the configuration of the mast and the horizontal arm of the crane (the jib) was greater than calculated by the design engineer. As a result, the crane bent further than expected. Consequently, the crane trolley, the travelling carriage on the jib to which the hoist cable is attached, sloped downwards. On 10 July at Prinsenlaan, this crane was hoisting one of the heaviest loads to date. The crane trolley moved the load along the jib, which was sloping downwards, into position. This slope required extra power from the engine that was controlling the crane trolley, but the engine was not designed for this purpose. In addition, several settings in the control of the engine were not correct. As a result, the engine was producing less than its maximum power and the brake was not used correctly. It was at that point in time that things went wrong. The crane trolley moved uncontrollably down the slope to the end of the jib. The load being hoisted became too heavy for the crane, which caused the crane to bend further and collapse.

The investigation into this incident has revealed that shortcomings in the design the crane were not identified and dealt with. Structurally searching for shortcomings in the design of cranes during the design phase using risk analysis is not part of general practice. Incidents that arise while using a tower crane are often not considered by the manufacturer as a sufficient reason to make changes to the design. Furthermore, there is no safeguard that helps to bring any shortcomings to light. Similar shortcomings could arise in the future, also for other manufacturers and for other types of cranes.

Public safety

Once every eighteen months there is an incident involving a tower crane that results in multiple injuries and fatalities. It is not only people on the construction site that run a risk, but also random passers-by and people who live or work in the area or use the area for recreational purposes. In 2003, a tower crane in Rotterdam fell on a building on the opposite side of the street. The building in question partially collapsed. One person died and one person was seriously injured. In 2007, a tower crane in Utrecht toppled over; the crane was located between several buildings. The crane fell on one of these buildings. Six university staff members were injured by falling debris. In both cases, the resulting damage was significant.

The size of tower cranes often means that the radius of the area where the crane could fall is greater than 100 metres. The Dutch Safety Board therefore considers it likely that people would be injured or killed if a tower crane collapsed, especially if the crane is located near areas where many people gather. Such situations are very common. Examples include the Zuidas area in Amsterdam and the train station areas in The Hague and Rotterdam.

Due to the high risk that literally hangs above people's heads, the Dutch Safety Board had expected the parties involved to make every possible effort to ensure that cranes function correctly. The Dutch Safety Board had expected that risk control and safety management with respect to the use of tower cranes would be well organised. However, the conclusion of this investigation is that this is not the case. The Dutch Safety Board therefore wonders whether passers-by can rightly walk by a tower crane unconcerned about safety, and whether construction workers and tower crane operators can safely perform their work.

CE mark through self-inspection

European product directives apply to tower cranes. These product directives establish general requirements for products. Specific requirements regarding the safety level of a product have been developed into standards. In following the directive, manufacturers themselves determine which standards apply to their products. If a manufacturer believes that its product complies with the directives and the safety level laid down in the standards, the manufacturer records this in a declaration: the EC Declaration of Conformity. In this declaration, the manufacturer also states which specific standards and directives apply to its product. In this case, this concerns standards for tower cranes. Once the declaration has been issued, the manufacturer may place a CE mark on the tower crane. This mark takes the form of a logo with the letters "CE", which stands for *Conformité Européenne.* That means that the manufacturer declares that its product conforms to European regulations and that its tower crane satisfies the product directives and underlying requirements. The crane does not need to be tested for quality and safety by any other party for this purpose. The manufacturer may now freely trade the tower crane in EU Member States, Iceland, Liechtenstein and Norway. These countries may not place any additional requirements on the tower crane.

The result of this working method within these regulations is that manufacturers themselves can declare that their product complies with the European product directives. However, manufacturers can make mistakes, such as in the design or the assessment of their design. Manufacturers can be less accurate or have insufficient in-house knowledge of certain subjects. The regulations do not provide for a safeguard that prevents tower cranes with potential safety shortcomings from being erected. As such, it is possible for a manufacturer to put an unsafe product on the market while customers, users and third parties mistakenly assume that it is safe.

This appears to have been the case in the Rotterdam incident of 10 July 2008. In the EC Declaration of Conformity, the manufacturer stated the directives and standards that it deemed to apply to its tower cranes. However, several of these standards and directives had been replaced by newer versions, or were not applicable to tower cranes at all. No risk analysis for the tower crane was available, and the investigation of the Dutch Safety Board revealed that the crane did not comply with the manufacturer's own design criteria. Based on these findings, the Dutch Safety Board concluded that the manufacturer had unjustly issued the EC Declaration of Conformity.

Periodic inspection with limited scope

Working conditions regulations apply when a tower crane is in use. These regulations state that tower cranes must be inspected before being put into operation, and at regular intervals after that. In the Netherlands, the assessment criteria for these inspections are laid down by the Foundation for the Supervision of Certification of Vertical Transport after approval by the Ministry of Social Affairs and Employment. These inspections assess the quality of the construction after erecting the tower crane and testing the crane with the maximum load to be lifted. However, malfunction reports, risks with respect to the functionality of the crane and the attention paid to interim maintenance are not addressed in these inspections.

According to the Dutch Safety Board, the inspection requirements and reports do not reflect the increased complexity of the sum of components from which a tower crane is assembled. The relationship with the configuration of a crane (height of the crane, the type of tower sections and the length of the jib) are not addressed either, while these aspects do have an influence on the stability, integrity and functioning of the crane.

The Dutch Safety Board has observed that any shortcomings that arise in the design or production phase of a tower crane potentially only come to light in the implementation phase due to malfunctions in practice. In other words: only when things go wrong. *Preventing* errors in the design, production and usage chain of tower cranes is not addressed or guaranteed in European product directives, nor in national legislation and regulations. A tower crane can be put on the market not only with shortcomings, but also in the absence of a subsequent safeguard for shortcomings that arose during the design and production processes.

Safety management principles inadequately applied

The Dutch Safety Board believes that manufacturers, owners and users each have their own responsibility with respect to the safe production, rental and use of tower cranes. That also applies if this responsibility is not expressly laid out in legislation and regulations. The Dutch Safety Board employs the principles of safety management[1] as a frame of reference for this. The application of these principles means that the manufacturer indicates which quality and safety requirements it applies to tower cranes. The manufacturer must explain how it has safeguarded the quality and safety of the design and production. The application of these principles also means, for example, that the design of a tower crane should be reviewed based on shortcomings identified in practice.

In the period prior to the Rotterdam incident on 10 July 2008, serious malfunctions occurred several times in cranes of the same brand. In these malfunctions, the crane trolley unintentionally rolled further than intended. This malfunction forms a serious threat to the stability of the tower crane. Each time this occurred, the manufacturer repaired and dealt with the malfunction for each crane in question. However, the manufacturer did not take any other measures with respect to other cranes: it did not modify the design, nor did it warn customers or users about the danger of this malfunction. In Rotterdam, the crane trolley rolling too far on 10 July 2008 ultimately resulted in the collapse of the crane.

The fact that signals from practice are not always addressed adequately also emerges from the report of the Health and Safety Inspectorate on the 2007 tower crane incident in Utrecht. Before the accident, the operator of this crane had observed that, when in its resting position, the crane did not always come to rest by itself in the same direction that the wind was blowing. In hindsight, insufficient action was taken in response to this observation, which could have served as a warning, and the crane fell over due in part to excessive wind stress.

Tower crane composition increasingly complex

Recent technological developments have led to modern tower cranes being assembled from increasingly complex elements. In particular, the developments in electronics and control are advancing very quickly. More and more specialist knowledge is needed to guarantee the correct functionality. The sections are delivered by various suppliers. As such, it becomes increasingly difficult to keep track of the consequences of assembling elements into a single tower crane. In the

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1 Principles of safety management: Understanding risks, employing a demonstrable and realistic approach to safety, implementing and maintaining this approach to safety, refining the approach to safety, and expressing the management's involvement by means of management and communication (see chapter 3).

certification scheme for the inspection requirements of tower cranes drawn up by the Foundation for the Supervision of Certification of Vertical Transport, the electronics and the control of tower cranes are addressed minimally, if at all. The functionality of the tower crane is therefore inadequately guaranteed in the inspection requirements.

The functionality of the tower crane was also inadequately guaranteed in the Rotterdam incident on 10 July 2008. The motor of crane trolley of the tower crane had limited power as a result of incorrect parameter settings of the frequency regulator, which drives the motor. Together with the jib bending further than allowed for in the design criteria, this led to the collapse of the crane.

Findings

The Dutch Safety Board has established that the CE mark gives customers and users the impression that everything is in order with the quality assurance of tower cranes, while this mark does not actually provide this guarantee. Customers and users mistakenly blindly trust the CE mark.

It surprises the Dutch Safety Board that tower cranes are not on the limitative list of dangerous machines, as stated in appendix IV of the Machinery Directive[1]. If this were the case, before the tower crane could be put on the market, its design would first have to be fully tested by a recognised inspection agency.

The Dutch Safety Board was also surprised to find that signals from practice are not always picked up or shared by users or manufacturers. Especially in a market where technological developments succeed each other so rapidly that it is hard for the knowledge development of individuals to keep pace, sector organisations, inspection agencies and major parties could join in a platform where such findings could be shared. Such a platform could function as a reporting office for accidents and near-accidents, and thus form an initial safeguard for identified shortcomings.

The United Kingdom

It is difficult to make a numerical comparison of incidents with tower cranes in the European Community countries, because these incidents are difficult to identify in data systems.

In recent years there have also been serious incidents with tower cranes in the UK. Tower cranes have also caught the express attention of the Health and Safety Executive (HSE). The HSE has communicated its great concern about the increase in the number of incidents, and has taken extensive measures. These measures focus on the education and training of people who work with tower cranes, on the performance of risk analyses and on testing and inspection.

The Dutch Safety Board and the HSE have jointly discussed their investigations and have established that there are similarities in the types of incidents in the Netherlands and the UK. While the causes of the last five incidents in each of the two countries are very different, there are striking similarities between the incidents themselves in both countries. In part, this concerns implementation aspects in the assembly (or increasing the height) and dismantling of the tower crane, but also the incomplete elaboration of new technological applications. Like the Dutch Safety Board, the HSE is concerned about the high speed with which new technological developments take place in the crane industry. The development of the sector does not keep equal pace with these

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[1] The Machinery Directive is one of the European product directives that apply to tower cranes. This will be discussed in more detail in this report.

developments. This problem requires a dual approach: sufficient consideration and elaboration of the tower crane product, and sharing and learning from identified shortcomings and accidents and near-accidents.

Taking the initiative to improve the situation

Further to this investigation, the Dutch Safety Board has directed three recommendations to the government and the Foundation for the Supervision of Certification of Vertical Transport. By doing so, the Dutch Safety Board intends to remove shortcomings in the guarantee of quality and safety in the use of tower cranes. To this end, the Dutch Safety Board is not alluding to one type of crane in relation to one incident, but to all tower cranes covered by the quality and safety supervision system in the Netherlands. In addition, the Dutch Safety Board recommends that efforts be made in a European context to include tower cranes in Appendix IV to the Machinery Directive.

With regard to the specific shortcomings of the tower crane in the Rotterdam incident, the Dutch Safety Board directly addressed the crane manufacturer. During the investigation, the Dutch Safety Board spoke with the manufacturer several times, and also informed and warned the manufacturer about a number of shortcomings.

In response to this incident, the manufacturer indicated that it has made improvements to this type of tower crane. The Dutch Safety Board did not investigate the extent to which the improvements made by the manufacturer have actually contributed to eliminating the shortcomings. The Dutch Safety Board sent a letter to the manufacturer urging the latter to bring its products and working methods in line with the principles of safety management[1], so that it is possible to assess the extent to which the measures implemented contribute to the stability and integrity of its tower cranes. Also in this letter, the Dutch Safety Board urged the manufacturer to contact its customers who had purchased tower cranes immediately and inform them of changes that are needed to guarantee the stability, integrity and safe use of the cranes.

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[1] Principles of safety management: Understanding risks, employing a demonstrable and realistic approach to safety, implementing and maintaining this approach to safety, refining the approach to safety, and expressing the management's involvement by means of management and communication (see chapter 3).

Recommendations

Based on its investigation, the Dutch Safety Board hereby makes the following recommendations.

Recommendations to the Minister of Social Affairs and Employment:

1. Ensure the establishment of a reporting office for accidents and near-accidents with cranes, including tower cranes. One of the goals of this reporting office is to warn all the parties involved of hazardous situations. This reporting office should be supported by a platform consisting of representatives from the sector: crane manufacturers and owners, users and clients.

2. In a European context, make a case for including tower cranes in the list of dangerous machines in Appendix IV to the Machinery Directive.

Recommendation to the Foundation for the Supervision of Certification of Vertical Transport:

3. Extend the certification scheme for tower cranes to include functional assessment criteria. These criteria should contain subjects that address electronic failures and failures in the control of the tower crane, as well as mechanical failures.

The Hague, November 2009

Prof. Pieter van Vollenhoven	M. Visser
Chairperson of the Dutch Safety Board	General Secretary

LIST OF ABBREVIATIONS AND TERMS

A	Rear jib	Horizontal arm of the crane on the side of the mast opposite from where the load hangs. The counterweight is placed at the end of the rear jib. The rear jib is therefore also called the counter jib.
B	Ballast	Material used as the counterweight. For the cranes in this investigation, these are, without exception, concrete blocks.
	BWT	Building and Housing Supervision Department (*Bouw en Woningtoezicht*) Municipal department that acts as the supervisory body for construction projects and other matters.
C	CAO	Dutch abbreviation for a collective labour agreement
	CE	*Conformité Européenne;* Indicates conformity with legislation based on European Product Directives.
	CE mark	Logo with the letters 'CE' that indicates that the manufacturer has issued an EC Declaration of Conformity for the product in question.
	Counterweight	Weight that is placed in the rear jib to ensure that the crane remains balanced, with and without a load.
	Counter jib	Horizontal arm of the crane on the side of the mast opposite from where the load hangs. A counterweight is placed at the end of the counter jib. The counter jib is also called the rear jib.
E	EEA	European Economic Area; Name for the free trade area between the EC Member States, Iceland, Liechtenstein and Norway.
	EC	European Community
	EC Declaration of Conformity	Declaration made by a manufacturer that a product, in the manufacturer's view, complies with all the European product directives applicable to the product in accordance with the legislation and regulations of the country where the manufacturer is located.
	FEM	Finite Element Method; Model for calculating the strength qualities of complex constructions.
	EMC	Electromagnetic compatibility; In the event of EMC, devices with electromagnetic fields operate without influencing each other.
F	Failure	Not meeting the established objectives.
G	Jib	Horizontal arm of the crane.
	GSM	Global System for Mobile Communications.
H	Load chart	The load chart is a chart that shows the maximum weight in tonnes for each jib length on each radius; for example, 14.8 tonnes on a radius of 25 metres for a jib length of 50 metres.
I	Moving inward	When the crane trolley moves over the jib towards the mast of the crane.
	Poured foundation	A concrete foundation poured in situ.
K	Trolley	Short for crane trolley. This is the travelling carriage that moves back and forth on wheels over the base of the jib. The hoist cable runs downward from the trolley. The crane trolley positions the load at the correct radius.
	Trolley cable	Cable that allows the crane trolley to move back and forth over the jib.
	Trolley winch	Drive gear that moves the trolley cable.

	Trolley stop	Arm pivoting around the middle of that arm with a weight at one end. The arm is held in horizontal position by the trolley cable. If the trolley cable breaks, then the arm is raised because of the weight. The arm is stopped by the props and bracket frames in the jib and is not able to move any farther to the front or the rear.
	KLPD	National Police Services Agency (*Korps Landelijke Politiediensten*)
	kN	kiloNewton; Weight unit to indicate the maximum lifting load.
	Crane	In this report, this refers to a tower crane, or: all crane components above the tower.
L	Load	The object of a certain weight to be lifted.
	Load moment	Torque; The load moment is determined by the weight and the radius of the load. The maximum allowed load moment is indicated in a crane's load chart.
	Load moment security system	Security system to prevent the maximum load moment from being exceeded.
	LMS	Load moment security system; Electronic security system that ensures that a load of a certain weight does not move further outwards on the jib than a specific set distance.
	Logic	Name for the correct sequence of cause and effect.
	Crane trolley	Travelling carriage that moves back and forth on wheels over the base of the jib. The hoist cable runs downward from the trolley. The crane trolley positions the load at the correct radius.
	Trolley tower crane	Tower crane with a horizontal jib and crane trolley.
	LVBT	National Traffic Assistance Team (*Landelijk Verkeersbijstandsteam*); Part of the KLPD.
M	Mast	Anchored vertical construction on which the crane rests, also called the tower.
N	NFI	Netherlands Forensic Institute
	Nm	Newtonmetre; Unit to indicate torque.
	NoBo	Notified Body; Independent accredited and designated inspection agency.
O	Accident scenario	Sequence of events in the incident.
	Peak up	In a tower crane: raising the tip of the jib.
P	PLC	Programmable Logic Controller; Programmable control system.
	Plug	Pin in a mortise and tenon connection.
	Control loop	Organised feedback around the life cycle of a product, in which findings from the usage phase are used to improve the design.
R	RI&E	Risk Inventory and Evaluation; A required tool to inventory and assess risks based on the Working Conditions Act.
S	Scenario	Theoretical sequence of events.
	SZW	Ministry of Social Affairs and Employment (*Sociale Zaken en Werkgelegenheid*).
T	TCF	Technical Construction File; Requirement from the EC Machinery Directive that involves the recording of technical data in a file, to demonstrate conformity with

		the applicable European product directives.
	TCVT	Foundation for the Supervision of Certification of Vertical Transport (*Stichting Toezicht Certificatie Verticaal Transport*);
		Foundation consisting of representatives from suppliers, users, employee representative organisations and the government, to establish inspection requirements for vertical transport.
	Tonne	1000 kilograms
	Tower	Anchored vertical construction on which the crane rests, also called the mast.
	Tower sections	Components from which the mast is assembled. For the crane in Rotterdam, these were 4.5-metre high parts whose tower legs were located over each other and secured using a plug (pin-hole connection). A caged ladder runs upward through the tower sections.
	Tower crane	In this report: a non-mobile crane that is built on site, consisting of a mast topped by a horizontal jib and crane trolley.
	Tower leg	One of the four standards on which a tower component is assembled.
U	Moving outward	When the crane trolley moves from the mast to the end of the jib.
V	V&G-plan	Health and Safety Plan (*Veiligheids- en Gezondheidsplan*);
		Plan that focuses attention on the health and safety of employees that work together on a construction site.
	Radius	Distance on the ground from the lifted load to the mast.
	Radius plan	Drawing on which the distances from the mast of the crane are indicated with concentric circles around the mast.
	Front jib	Horizontal arm of the crane on the side of the mast where the load hangs.
	VROM	Ministry of Housing, Spatial Planning and the Environment (*Volkshuisvesting, Ruimtelijke Ordening en Milieubeheer)*.

1. INTRODUCTION

The Dutch Safety Board conducts independent investigations into incidents and accidents, with the goal of making a contribution to preventing such occurrences in the future. Based on its social responsibility, the Board itself determines which incidents are investigated. On the basis of the investigation, the Board makes recommendations for measures that will create a safer society. In this report, the Dutch Safety Board is reporting on the investigation conducted following the collapse of a tower crane.

1.1 REASON FOR THE INVESTIGATION

Op 10 July 2008, a tower crane collapsed on a construction site at Prinsenlaan in Rotterdam. The crane operator died in this accident. In recent years in the Netherlands, incidents involving construction cranes[1] have caused an average of seven fatalities and several injuries per year. Points of attention for the Dutch Safety Board arising from these incidents include the improved assembly and stability of the crane in relation to the safety of the surrounding area. In view of the seriousness of the incident on 10 July 2008, the Dutch Safety Board decided to perform an investigation on site. The first findings from this on-site investigation indicated that the tower crane may have collapsed as a result of overloading. It immediately became clear how much energy can be released when a tower cane collapses, and what consequences this could have for people in the surrounding area. The Dutch Safety Board's concern therefore also emerges from the fact that, in countless places in the Netherlands, tower cranes are erected on large urban construction sites in such a way that the crane operator, construction workers and the public in public areas run a risk in the event that the crane collapses. Based on these considerations, the Board decided to conduct a formal investigation into this incident.

1.2 OBJECTIVES OF THE INVESTIGATION

In the investigation that is the basis for this report, the Dutch Safety Board focused on answering the question of how the tower crane in Rotterdam could have collapsed and what failure mechanisms formed the basis for this. Failure mechanisms are the events and facts that, collectively or separately, can lead to undesirable events occurring. In addition, the Dutch Safety Board investigated what barriers could have prevented these failure mechanisms from occurring, and why these were not in place or why they did not work.

The objectives of this investigation are as follows:

1. To determine the cause of the collapse of the tower crane at Prinsenlaan in Rotterdam;
2. To bring to light any possible shortcomings in the design of the tower crane;
3. To identify a safeguard (or lack thereof) that could identify and help prevent accidents resulting from shortcomings in design or production.

1.3 SCOPE AND WORKING METHOD

The facts from the initial investigation at the Prinsenlaan site in Rotterdam revealed that the method of hooking the load and the procedures around crane activities in the construction sector did not contribute to the collapse of the crane. Therefore, in this investigation, the Dutch Safety Board focuses on the potential failure mechanisms that were implicit in the design of the crane and that could have served as the basis for the collapse of the crane.

There are various types of tower crane, each with its own characteristics. The crane that collapsed was a tower crane with a horizontal arm, the jib, on which a crane trolley rolls back and forth. The investigation is limited to this type of trolley tower crane (see chapter 2 for further details).

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[1] This concerns tower cranes, mobile tower cranes and mobile telescope cranes. Data compiled from information from the Health and Safety Inspectorate.

Tower cranes are usually erected on a construction site and remain there for a longer period (several months, and often more than a year). Mobile tower cranes and mobile telescope cranes are usually located on a site for a much shorter time (one day or several days) and can be erected by workers themselves. Tower cranes, however, are erected using mobile cranes. In this investigation, therefore, the Dutch Safety Board focuses solely on trolley tower cranes which are erected on a construction site. Cranes with a permanent location, such as in harbours or in transfer areas, fall outside the scope of this investigation.

To determine the cause of the accident, various partial investigations and activities were performed. In addition to the Dutch Safety Board, the Health and Safety Inspectorate conducted an investigation into this incident on behalf of the Public Prosecutions Department. The investigation of the Health and Safety Inspectorate had not yet been completed when this report was published.

For parts of the technical investigation, the Health and Safety Inspectorate and the Dutch Safety Board jointly, and in mutual coordination, made use of the expertise of Aboma Keboma and the Netherlands Forensic Institute (NFI) and, for the destructive material expertise investigation, the expertise of Schielab. On behalf of the Dutch Safety Board, supplementary studies were conducted by FEMTO Engineering, Dare Consultancy and D&F Consulting (see Appendix A).

1.4 STRUCTURE OF THIS REPORT

This report concerns an incident with a trolley tower crane. Chapter 2 discusses the factual information that is used in this investigation, and starts with an explanation of tower cranes in section 2.1. This general explanation is supplemented with information on the crane particular to this investigation. This is followed by a description in section 2.2 of the incident on 10 July 2008 at Prinsenlaan in Rotterdam. The findings from the partial investigations are discussed after this. Section 2.3 discusses the findings from the damage profile of the crane that collapsed. Section 2.4 describes the findings from an investigation of four cranes of the same brand and type on other construction sites in the Netherlands.

After the factual information, chapter 3 sets out the assessment framework that the Dutch Safety Board uses to position and analyse the incident. This framework contains legislation and regulations in addition to a framework of internationally accepted principles that the Dutch Safety Board uses to flesh out the principle of individual responsibility with respect to safety management.

Chapter 4 describes the parties involved and their responsibilities and mutual relationships. This investigation involves three networks of parties, which are interconnected to a limited extent.

Based on the data from chapters 2, 3 and 4, chapter 5 contains the Dutch Safety Board’s analysis. Section 5.1 discusses three possible scenarios for the collapse of the tower crane. Section 5.2 further elaborates the most probable scenario into sub-scenarios with a discussion of the failure mechanisms that may have played a role. Section 5.3 then discusses the possible barriers against these failure mechanisms. Section 5.4 subsequently addresses the use and the knowledge of tower cranes in practice, and includes a discussion of four previous incidents with tower cranes. Section 5.5 sets up the conclusions (chapter 6) and recommendations (chapter 7).

For reasons of clarity, Appendix F (the last page of the report) contains a tower crane diagram, which specifies all the parts of the tower crane.

2 FACTUAL INFORMATION

This chapter provides a summary of the factual information that is necessary to understand the incident and the investigation. Partial investigations performed on behalf of the Dutch Safety Board are included in the appendices where necessary. This chapter describes general characteristics of tower cranes and offers a more detailed description of the tower crane involved in the incident. The chapter also provides general description of the environment where the crane was erected and who was using the crane. This is followed by a description of the incident and the findings from the investigations carried out after the incident.

2.1 TOWER CRANES

2.1.1 General

There are many types and sizes of tower cranes. In this investigation, the Dutch Safety Board focuses on non-mobile cranes on a tower. The Board makes a distinction in this context between two types of cranes: cranes with a moveable jib, the so-called luffing jib cranes, and cranes with a fixed jib, trolley tower cranes. This investigation concerns trolley tower cranes. Where this report mentions 'tower cranes', trolley tower cranes are meant specifically. Trolley tower cranes have a predominantly horizontal arm, which is called a jib, on which a carriage (crane trolley) rolls back and forth. Luffing jib cranes generally have a jib with a pivot point close to the mast. Using a guy construction (cables), the jib can be raised or lowered. In the Netherlands, luffing jib cranes are often used at permanent positions in loading and unloading areas, such as harbours, but they are also used as construction cranes. These luffing jib cranes were not included in the investigation in this report.

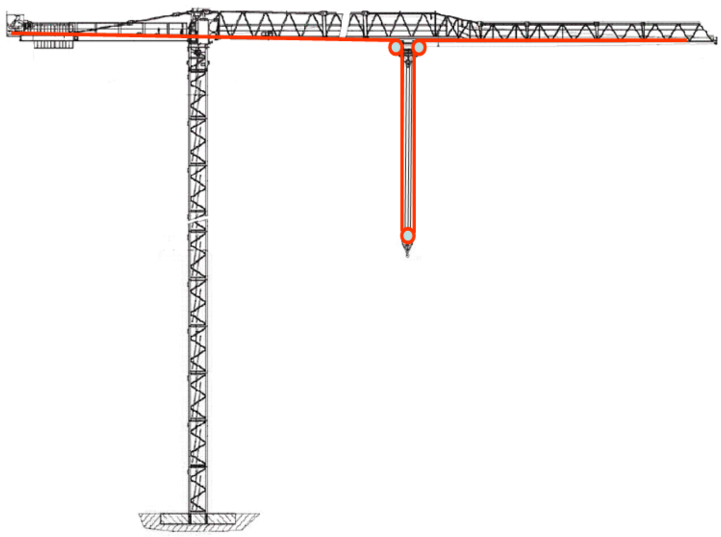

Figure 1 - Simplified illustration of hoist cable

The jib of a trolley tower crane consists of two parts, the front jib, where the hoisting takes place, and the counter jib or rear jib, where the end of a heavy ballast is placed to keep the crane in balance while it is lifting the load. Two cables run through the jib. In a trolley tower crane, the hoist cable runs from the lifting drum up the back to the rear jib to the front, over a disc in a block (a "pulley") on the crane trolley, and then downwards through a block on the hook. The cable runs on the front of the block on the hook back up again, then is guided through a second block in the trolley, and then runs to the front to the tip of the jib where it is secured (Figure 1).

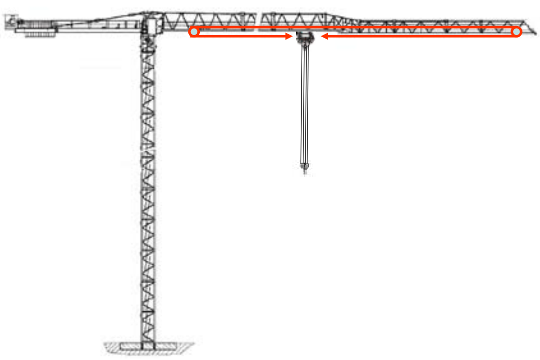

Figure 2 – Simplified illustration of trolley cable

The second cable is used to move the crane trolley over the jib. The cable is secured on the front of the crane trolley, runs over a disc through a block on the front of the jib, then returns to the back through the winch drum, also over disc through a block, and is then secured again on the back of the crane trolley (Figure 2). This trolley cable is driven by an electric motor that is connected to the trolley winch drum. The motor is controlled by a frequency regulator.

The tower crane that was the cause for this investigation is from a series of new models of trolley cranes. The models in this series are characterised by the fact that the cranes, with the exception of the heaviest models, do not have a top. This means that the tower does not extend above the jib. On tower cranes that do have a top, guy lines run from the top of the top to the front and rear jib. These guy lines make the jib more rigid. According to the manufacturer, tower cranes without a top can be effectively used "*in places where there are height limitations*", such as in a situation where several cranes are located near each other and pivot over each other. This need was not present at the Rotterdam site. Another advantage of a tower crane without a top, according to the manufacturer, is that this type is easier to transport.

All the cranes in the series have a tapered jib with a crane trolley with a double drive system (see Figure 3). The tapering causes the girders of the job over which the crane trolley moves, to move downwards and to the inside. The crane trolley moves over the jib with the top set of four wheels. When moving to the outside, the lower set of four wheels takes over on the tapered jib. The tapered jib is lighter and can be slid into the larger jib parts during transport.

Figure 3 Crane trolley with double drive system

The tower cranes are mounted on a moving undercarriage, a fixed undercarriage, or a foundation poured in situ[1]. The mast is composed of stacked tower components. The square tower components consist of four standards on each corner, the tower legs, and kept in shape by cross-girders and diagonals. The tower components vary in strength and weight. A caged ladder runs through each tower component to an upper landing. In the Netherlands, if the climbing height to the cab is 30 metres or more, an operator's lift is installed in accordance with CAO rules. For each crane configuration, the design engineer determines which tower components are used. At the top of the tower is a tower component that is part of the crane in question, with a turntable, the tower ring. There is a manhole in the ring, which the operator can use to climb to the top. The jib/front jib, rear jib and the cab are hung on the tower component above the ring. This tower component is called the top. Because this top does not extend beyond the jib, the crane is called a 'topless' crane.

2.1.2 The crane at the construction site in Rotterdam

The tower crane in Rotterdam was located on a small construction site in a park. A walking and cycling path runs along this location, and a children's play area is also situated in the park. A wide ditch borders the north side of the site. The construction site was connected to the public road by means of a bridge over this ditch. A 24-storey block of flats with 80 apartments was being built on this construction site. Under the block of flats, a two-storey parking garage was being built under ground level. In the excavated area, a poured foundation was made for the tower crane when the foundation and the floor of the lowest storey were installed. When the garage roof was closed, working space was created around the building. The crane was located on the east side of the building. In the investigation, the east side was referred to as the back of the crane (number 1 in Figure 5) and the south side was referred to as the left side (number 2 in Figure 5). The operator's lift was installed on the back side.

The bottom tower component was anchored on the poured foundation and supported twelve of the same tower components on top of it. On this tower, the new crane—direct from the factory—was erected by the new owner, with the cooperation of the manufacturer. This crane was 60 metres high. On 24 August 2007, the erected crane was approved for use by an accredited inspection

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1 Poured foundation: a concrete foundation poured in situ.

agency, using an assessment form for the periodic investigation and testing of tower cranes. This document also stated that this was the first usage inspection.

After slightly less than a year, the mast was increased to 96 metres. The crane was partially disassembled and hoisted from the vertical mast. At the eleventh tower component (counted from below), the mast was anchored to the outside wall of the block of flats being built. The concrete construction around the anchoring was adapted to this. Next, a transition piece was placed on the tower so that seven lighter tower components could be assembled on top. The crane was then re-erected to a height of 96 metres. After the height had been increased, the crane was recertified by the same agency on 23 June 2008, using the certification scheme for the certificate of approval for the periodic inspection of a tower crane. This certificate was issued, on condition that a lifting test with the maximum load of 16 tonnes would be conducted once a new hoist cable was reeved. On 3 July 2008, the owner confirmed to the inspection agency that this had been done.

2.2 COURSE OF EVENTS IN THE INCIDENT

On Thursday 10 July 2008, the contractor's plan was to hoist a balcony slab at the construction site. The crane had already hoisted the same balcony parts to the lower stories before its height had been increased. The balcony, with the pre-mounted fall safety device, weighed 7.3 tonnes. A balancing device was used to hoist the balcony to the intended position. This is an arm with a weight that hangs on the lifting hook. The load is suspended from this arm, so that it ends up hanging eccentrically under the hook. This allowed to balcony slab to be hoisted under the protruding end wall scaffolding. The balancing device itself weighed 5.5 tonnes; therefore the total load was almost 13 tonnes. Because of the high weight of this load, the subcontractor had decided not to hoist it over the building, and to only lift the load when the people on the construction site were in the hut or were taking a break inside the lower part of the building. The good weather and the moderate southerly wind were favourable for hoisting a large, heavy load.

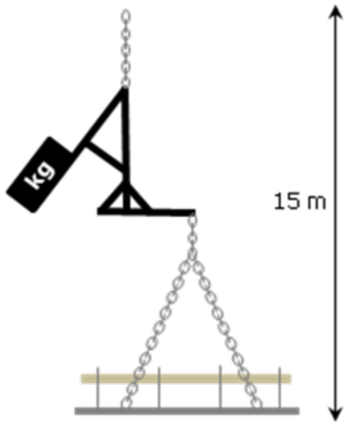

Figure 4 – Diagram of the lifted load: balancing device (black) with balcony on 4-way chain

The balcony was loaded under the balance with a four-way chain (four chains on one lifting eye) by one of the workers on the construction site (number 3 in Figure 5 on the next page). He was in contact with the crane operator by walkie-talkie. Three men with walkie-talkies were waiting at the intended location of the balcony on the eleventh floor (number 4 in Figure 5). The operator turned the crane to the right, which hoisted the balcony clockwise towards the building. At the level of the farthest corner (number 5 in Figure 5), it appeared that the crane trolley was unable to move far enough to the outside on the jib to lift the load around the corner of the building. The load moment security system (LMS) in the software of the crane will decelerate[1] and stop the crane trolley

[1] If, when moving outward, the crane trolley attains 90% of the maximum load moment, the movement outward is slowed down to prevent an abrupt stop and a warning signal sounds. When 100% is reached, the

moving outward if a certain weight in the hook reaches the maximum allowed radius on the jib. The operator therefore hoisted the load over the building and brought it down in the corner where the balcony was to be installed. At the point when the balcony was almost at its intended spot, the men in the building said that operator should not move outwards, but inwards, after they had seen the crane trolley (briefly) move towards the point of the jib. The operator indicated that he was not moving the load outwards. At that point, the load was hanging at a radius of approximately 27 metres. The three men then saw the load sway away from them, and the crane collapsed.

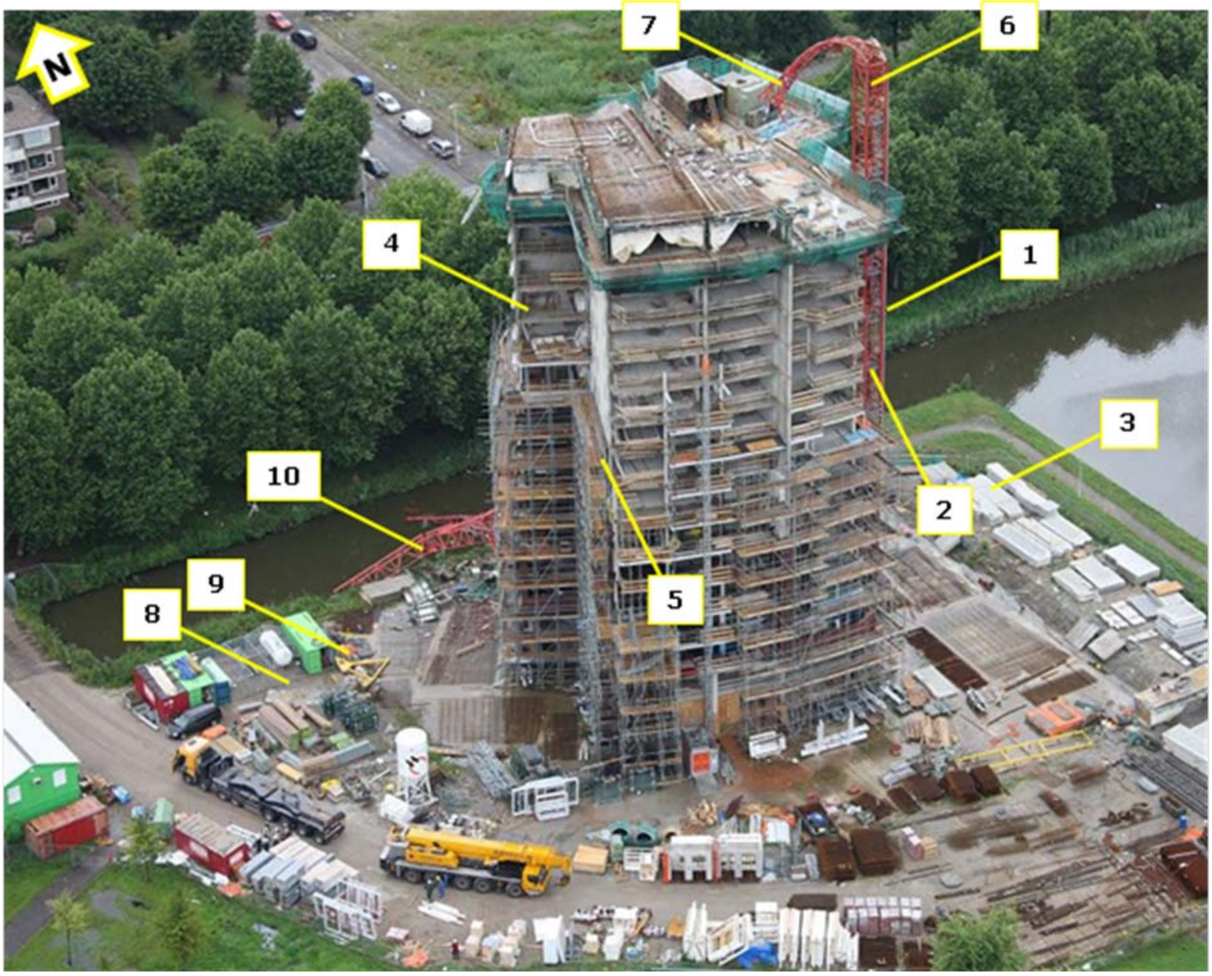

Figure 5 – *Overview photo of the construction after the collapse of the crane (source: KLPD Dienst Luchtvaart)*

The investigation revealed that the tower of the crane collapsed due to a load that was too heavy on a radius that was too large. The load (the balancing device and the balcony – Figure 4) unintentionally moved to the end of the jib, as a result of which more weight ended up on the tip of the jib than the crane could manage[1]. The mast of the crane bent as a result, which led to the front (the side of the jib) being pressed down, and the back (the side of the rear jib) being pushed out. As a result of this stress, the tower leg directly in front buckled, which caused the crane to fold over (number 6 in Figure 5). The tower leg at the left rear ripped off due to the tension strain. Both the other tower legs served as pivots. As a result of the bending, the rear jib with the counterweight came up and then dropped to the side. The immense stress on the steel construction caused the mast above the bend to violently tear off of all four of the tower legs (number 7 in Figure 5). The crane tumbled and fell to the ground. The lifting drum then knocked a hole in the concrete on the north side of the building, and various parts of the scaffolding were hit

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outward movement of the crane trolley stops. The design of the crane assumes that the crane can withstand 150% of the maximum allowed load indicated in the load chart. If this maximum allowed load is exceeded, the crane will collapse.

[1] This analysis is elaborated in chapter 5.

and damaged. The balcony slab fell to the ground in line with the position of the jib (number 8 in Figure 5), with the balancing device close by (number 9 in Figure 5). The crane ended up on the north side of the building, and the jib with the crane trolley fell in the water (number 10 in Figure 5).

When the crane collapsed, the operator may have fallen through the front window of his cab. He fell 40 metres onto the top floor of the building, and died immediately.

2.3 Facts and findings emerging from the partial investigations

2.3.1 General

The Dutch Safety Board launched its investigation immediately after the accident, followed the day after the accident by the Public Prosecution Service. The two parties acted in coordination to collect the factual data (see also Appendix A – Explanation of the Investigation).

Before work could commence on recovering the crane, loose material was removed from the sides of the scaffolding, the end-wall scaffolding and the building. After several days, when it was safe to work, the switch box and the operator's cab, with the electronics and possible data carriers that it contained, were recovered. They were stored by the Netherlands Forensic Institute (NFI) under protected conditions and subjected to investigation. Next, the separate parts of the crane were recovered. Each part was photographed and scanned by the investigators involved and by the Forensic Investigations team of the Rotterdam Rijnmond police department. Various distances and lengths were also measured, as were parts of the load. Further investigations were conducted based on the findings emerging from the recovery. The sections below describe those findings.

2.3.2 Damage profile

Position and data relating to the load

The load hoisted at the moment of the incident consisted of a concrete balcony slab with premounted fall protection in the form of fencing. The combined weight of the burden was measured at 12.8 tonnes. The total reduction of the hoisted height, the length below the hook, was approximately 15 metres (see Figure 4 on page 21).

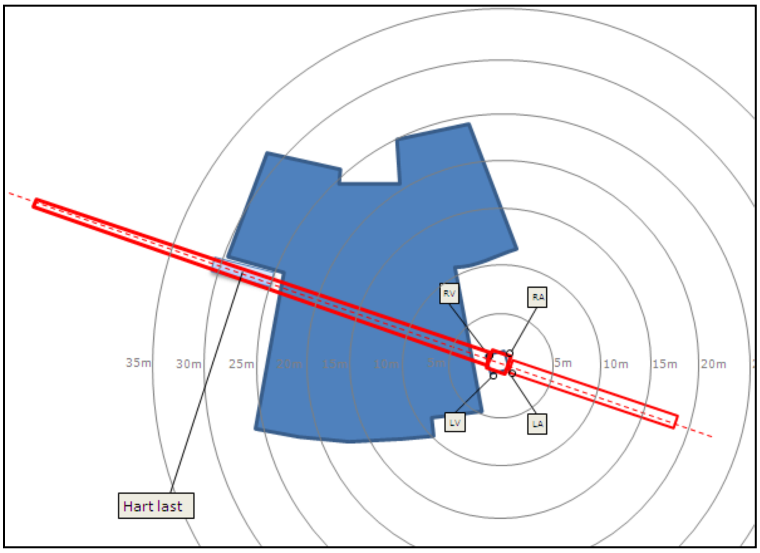

Figure 6 - Overview of radius of the tower crane at the construction site, showing the position of the tower legs; RV – front right, RA – rear right, LV – front left and LA - rear left (source: Aboma Keboma).

After the length of the hoist cable had been reconstructed, calculations showed that the height of the load was virtually identical to the height of the floor on the level where the balcony was to be placed, around 40 metres above the basement floor. To calculate the radius, i.e. the distance from the hoisting hook to the crane's mast, the distance on the ground was measured, from the heart of the mounted balcony to the crane. This came to 26 metres. As the load was not yet attached to the building, the radius at the time is estimated at around 27 metres. This matches the statements from witnesses. The radius is shown in Figure 6. According to the load chart provided with the crane, the maximum radius for 13 tonnes was 28 metres.

Profile of the damage to mast sections and fractures

The crane's mast was made up of three types of mast sections, in accordance with the configuration specified by the manufacturer's design engineer. The bottom thirteen mast sections were constructed to be heavier than the top seven mast sections. A transitional section was situated between those mast sections. Each of these mast sections was 4.5 metres in length. The third section below the transitional part, i.e. the eleventh mast section from the bottom, was anchored to the building being built, at a height of 48 metres above the foundations.

Figure 7 - Bent, broken and torn mast
(Photo: Rotterdam Rijnmond police department)

After the crane collapsed, all mast sections up to and including the transitional section were still upright, having suffered no visible damage. The first mast section above the transitional section was bent. The left rear tower leg (see Figure 6 for the designations of the tower legs) had broken loose at the mortise and tenon connection at the bottom (58.5 metres above the foundations). The upper part of the first mast section above the transitional section was bent completely out of shape, as were the next two sections. The tower legs, which normally form a square, were now positioned in the shape of a diamond shape in relation to one another, approximating a flat surface. The uppermost of those deformed parts, the third mast section, had torn loose at all four tower legs. The left front tower leg was visibly buckled.

Profile of the damage to the jib, trolley winch unit and hoist cable

The front jib fell into the water. During the recovery, it became apparent that the trolley had shifted to the end of the jib. The catches, which should have prevented the trolley from running along the jib, did not display a great deal of damage. The trolley itself was barely damaged at all, nor was the trolley cable broken. The trolley stop, an arm that is held in horizontal position by tension on the trolley cable, was also intact. Had the trolley cable been broken, a weight would have forced the arm up. If the trolley had run out, it would have been caught by one of the cross girders. The trolley motor was still intact after the fall.

After the accident, the hoist cable was found lying next to the discs in the trolley's blocks. Traces on the synthetic blocks revealed that although the hoist cable hit the blocks during the fall, the damage was superficial. If a weight had been hoisted while the hoist cable was running off the discs, the damage to the discs would have been much greater. The buckles in the hoist cable were caused during the fall, at the moment that the load hit the ground. The hoist cable started to twist when it was suddenly relieved of its load. This has been qualified as consequential damage.

The connecting section of the tension rod connecting the front jib to the top (topping the jib) had been bent by the fall. No traces of overloading were detected on the tension rod. Similarly, no traces of overloading were identified on the Y profiles in the masthead, which serve to draw off the forces that the jib exercises on the top.

Profile of the damage to the cab and switch box

The switch box and the hoist cable's drum were both positioned at the rear of the rear jib. The damage to these parts revealed that they hit the building. The switch box came loose from the jib and fell to the ground separately. The doors to the switch box had been broken away, as had the

GSM aerial mounted in the switch box. The switch box and all its parts were damaged. An investigation of the settings of the switches shows that the crane was operating in normal mode.

The cab was very heavily damaged. It hit the ground separately from the top. The whole cab had been compacted by the impact of the fall and possibly also by the falling part of the tower. The emergency button in the cab was found in depressed position. It is impossible to determine whether the operator managed to press the emergency button or whether it was caused when the cab compacted.

2.3.3 Investigation of other tower cranes

To view the findings of this case in their proper perspective, an investigation was conducted using current tower cranes of the same brand and type. Those cranes were erected on building sites in Rotterdam, The Hague, Amsterdam and Zaandam. Some of the findings from those local investigations have bearing on this investigation. The investigations focused on electromagnetic malfunctions in the crane's cables and connections, its operating systems and the bend and strength of the crane's construction.

Electromagnetic Compatibility

In this type of tower crane, the switch box is mounted at the end of the rear jib. This means that the power cables and data cables run along the rear jib for a distance of approximately 20 metres. The investigators found them lying consistently in a single bundle along one side of the jib. The electromagnetic field generated by power cables means that those cables can affect data cables. This situation may arise if the cables are located close together or are not protected sufficiently from this interference, which may cause malfunctions in the crane's operation. The Dutch Safety Board instructed a certified inspection agency in this field, Dare Consultancy of Woerden, to investigate this interference. Dare carried out that investigation by taking measurements along the cables of a crane whose trolley motor and hoisting motor were both supplying power, by hoisting or lowering and moving in or out at the same time. Dare compared the measurements with the standards corresponding to the European Electromagnetic Compatibility Directive (EMC Directive).

Malfunctions arose during Dare's testing, with Aboma Keboma's assistance. Those malfunctions became visible in the form of messages on the operator's monitor. However, those error messages did not in all instances prompt the Programmable Logic Controller (PLC – the control program) to take measures. The system is not programmed in such a manner as to ensure that every error message leads to a safe action. Not performing certain instructions and deactivating the crane are examples of such safe actions. This means that the crane can still be operated after an error has been given, despite something being wrong. Nothing was found that indicated that the malfunctions caused other commands besides those given by the operator to be performed.

During the test it was found that incorrect information about the weight of the load appeared on the monitor, caused by a consciously generated malfunction in the form of the generation of an electromagnetic field. This observation was followed by an error message about the designated weight, while all actions such as lowering, hoisting and moving in and out remained possible. Under those circumstances, it is possible for the crane to hoist too great a load to too great a span, without the load moment security system being activated.

Measurements for the bend of the mast and jib

Tower cranes move, and they are elastic to a degree and as a result flexible. Tower cranes of the type that collapsed in Rotterdam are known for their flexibility. The investigators have found that this type of crane is indeed flexible, even compared with the manufacturer's specifications. That flexibility was mapped out by the National Traffic Assistance Team LVBT of the National Police Services Agency KLPD, at the instructions of the Dutch Safety Board, using measurements with laser equipment. Measurements were performed on the crane that was erected at the site of the accident. The composition of that crane's tower was different, more rigid, than that of the original crane. Those measurements revealed that even with this more rigid configuration the crane bent further than the manufacturer's assumptions.

2.3.4 External investigation

Investigation into the materials of the tower legs

One of the possible scenarios for the crane's collapse is that the crane's mast was not strong enough, for example as a result of material failure. To demonstrate this, Schielab laboratory in Rotterdam conducted an investigation at Aboma Keboma's instructions. That investigation was conducted at the request of the Dutch Safety Board, and was coordinated with the Public Prosecution Service. Schielab set up a destructive materials investigation of the tower legs and cross beams of the damaged mast pieces. Staff of Schielab visited the site of the accident to examine the crane's situation. After the parts of the crane had been recovered and secured, they cut out samples. Schielab then subjected those samples to tensile tests and materials investigation to determine the quality of the steel used. Schielab also examined the fractures under a microscope.

Models of the strength of the mast and jib

Models of the tower crane that collapsed and the new tower crane built in its stead were created using the manufacturer's detailed drawings. This work was carried out by FEMTO Engineering of Delft, at the instructions of the Dutch Safety Board. FEMTO created computer models of the two cranes, based on the Finite Element Method (FEM). The FEM is a numerical method that is used for calculating the strength characteristics of complex constructions. That model was applied to the newly constructed crane, and compared with the measurement data provided by the LVBT. The LVBT's measurements were virtually identical to the predicted bend generated by FEMTO's computer model. The configuration of the crane that collapsed was then subjected to the same calculations.

Trolley motor and frequency regulator

The jib's bend gives the jib's surface a downward angle sloping down to the jib's tip. To prevent the trolley from running out when it should not, the amount of bend is limited and the motor and brake transmission of the trolley motor must be capable of holding the trolley and its load in place, or even moving it ‘upward’, while at an angle.

The investigation also included a tensile test of the trolley motor's brake transmission. That test revealed that approximately 14kN is needed force the trolley cable drum through the brake. This means that if a force of 14kN is on the trolley cable, the trolley cable drum's brake will no longer hold the trolley cable (or the trolley). Aboma Keboma calculated that if the trolley is already in motion the dynamic brake power of the brake is around 12kN, i.e. 15% less.

The trolley motor was controlled using a frequency regulator. Various parameters have to be set for each use of a frequency regulator, such as controlling a trolley motor. The findings arising from the investigation reveal that the parameters had been set in such a manner that the trolley motor could not always provide the power needed.

The manufacturer of the frequency regulator used in the tower crane calculated the torque needed to hold the trolley in place with a load of 13 tonnes. At an angle of 2 degrees, this is 48.45 Nm. At an angle of 2.5 degrees, this is 56.88 Nm. The maximum torque provided by the motor was 49 Nm.

This means that the maximum power of the motor with the frequency regulator is very close to the power required under the conditions under which the crane in Rotterdam was constructed.

Working of the Programmable Logic Controller

Aboma Keboma also investigated the crane's control program. The instructions that the operator gives, using the joysticks, are transmitted by the *Programmable Logic Controller* (PLC – the operating system). Before this happens, the system checks whether all programmed conditions are met. Such conditions take the form of logic rules, meaning that they are very much black-andwhite: either the condition is met, or it is not. The load moment security system is an example of such a series of conditions.

To determine whether the conditions are met, input from other systems is needed. For the load moment security, these are the positional indicators for the trolley and the measuring axle around which the hoist cable runs. The commands to hoist and move out are carried out if the combination of the load's weight and the radius fall within the range permitted. Every time a tower crane is re-erected, an inspection agency tests whether the load moment security system has been programmed correctly and responds properly. If the load moment security system works as it should, the crane in this investigation will not hoist a weight of 18 tonnes, and a hoisted weight of 13 tonnes will not extend to a radius of 40 metres.

When the operator gives the command to hoist or move out, the PLC checks the conditions for the load moment security system. If the load moment security system is activated, but no input is received from the measuring axle or the positional indicator, the logic is that the commands for hoisting and moving out will not be carried out or else will stop while being carried out. Error messages for the input are also processed in this manner. A double measuring axle was fitted. If the difference in measurement between those two measuring axles, if any, exceeds a certain margin, this would produce an error message and nothing would be hoisted or moved out. Nothing has emerged to indicate that this error, which occurred during the EMC tests in Amsterdam for example, occurred in the crane at Prinsenlaan on 10 July 2008.

2.4 ACCIDENTS WITH TOWER CRANES

2.4.1 Incidents in the Netherlands

For purposes of comparison, the Dutch Safety Board studied other accidents in the Netherlands that involved tower cranes and selected the following four incidents.

Cuijk, 31 October 2002

In the town of Cuijk, a tower crane fell over while being erected. There were two fatalities and one person was severely injured. The crane fell over when the ring was turned to fasten the jib after the rear jib was attached. This occurred because the concrete block on which the crane was erected was incapable of properly transmitting the forces to the ground below. The concrete block's surface was not large enough, causing it to sink. The risk calculation performed before the requisite surface for the concrete block was determined had used incorrect assumptions. The court judged that the correct assumptions could have been made if the NEN-6700 standard for “technical principles for building constructions” had been used.

Rotterdam Brielselaan, 2 December 2003

A 79-metre freestanding tower crane was used to pour concrete for a residential tower block that was being constructed. The crane fell over, landing across the public road on top of a former grain warehouse that had been converted into an exhibition and convention centre. The operator was severely injured. The counterjib fell on the roof of a foodstuffs business. One floor collapsed. One employee was killed in the building, and another was severely injured. The damage to the buildings was substantial. The investigation revealed that the nuts on the bolts used to anchor the crane were not tightened sufficiently at the time of the accident. The bolts gave way, causing the crane to unbalance and fall over.

Utrecht, 18 January 2007

A 63-metre tower crane had been erected near two high buildings belonging to Utrecht University. On 18 January 2007, a stormy wind caused turbulence around those buildings. At the height of the jib, the winds attained storm force. The crane was unmanned and in weathervane mode. If a crane is in weathervane mode, this means that the jib can move freely with the wind, like a weather vane. The rear jib will then face the wind. However, the interaction of the lee and turbulence prevented this crane from attaining the correct weathervane position. In this case, the jib was positioned into the wind, and the crane was less balanced. The operator had already noticed this phenomenon on an earlier occasion. The turbulence moved the tower crane's jib both vertically and horizontally. The dynamic forces increased the pressure on the foot of the mast to more than the breaking strength of one of the wrought heads in the foundation, which broke, causing the crane to fall over backwards. The jib landed on another university building nearby, causing its roof to collapse. Six people in the building were hurt. The investigation into the wrought heads revealed that the wrought heads did not meet the applicable specifications.

Horst, 20 July 2007

In June 2007, a crane was erected on a building site in Horst. It was intended to be replaced by a heavier crane as soon as one was available. The crane was on a mast, and anchored on a cross frame with a 20-tonne ballast. The cranes were switched on 20 July 2007. When the rear jib of the new crane had been turned to allow the jib to be attached, it fell over. Two people were injured. The investigation revealed that a 60-tonne ballast should have been used for the new crane. Since the crane's owner had 40 tonnes of ballast available, another 20 tonnes of extra ballast had been ordered from the manufacturer by fax. Subsequently, those 20 tonnes were mistakenly held to be the weight that was to be used. The manufacturer's instructions were not read when the new crane was erected. The new crane's log was also incomplete and did not include, among other things, the instructions for the amount of ballast needed.

2.4.2 Incident in Germany during the investigation

On 4 November 2008, there was an incident in Munich (Germany) with a crane similar to the one at Prinsenlaan in Rotterdam. In the crane's top, two adjacent profiles in the form of the Greek letter 'λ' (lambda) transmit the forces from the front jib to the mast. One of the two 'legs' of that λ tore, in each of the profiles. The jib bent sharply downwards, though the crane did not collapse. The cause of this incident is believed to be poor welding in the construction of the λ profile. All cranes in the series of cranes where this problem might occur have been investigated, and if any doubts emerged about the quality they were welded again.

3 ASSESSMENT FRAMEWORK

3.1 INTRODUCTION

The Dutch Safety Board uses an assessment framework for its investigations. Based on that framework, the Safety Board analyses the events of and backgrounds to the incident. By identifying deviations from the assessment framework, the Safety Board can show where improvements are possible or necessary.

The assessment framework for this report consists of three parts. The first part comprises the laws and regulations that applied to the activities related to the incident. The second part is industry-oriented, and comprises the way in which regulations are put into practice in the form of certification schedules for inspecting tower cranes. The third part is the Dutch Safety Board's own assessment framework, comprising a series of internationally accepted principles that the Dutch Safety Board uses to give shape to its own responsibility in the field of safety management.

One factor that complicates the consideration of the section concerning laws and regulations is that the tower crane was built in Germany, under German laws and regulations. The German laws and regulations for development and sales are based on the same European Directives as the Dutch laws. As such, those European Directives form an important part of the assessment framework. Appendix E to this report provides further details to the sections set out below.

3.2 EUROPEAN DIRECTIVES AND THE CE MARK

3.2.1 General

The European Community (EC) imposes standards on the sale of products. To prevent restrictions on free trade caused by differences in safety requirements in the EC's Member States, those standards are laid down in European Product Directives. The Member States are obliged to implement the European Product Directives in their national laws: the Directives are applied by way of national legislation. In the Netherlands, the Directives have been incorporated into various Commodities Act decrees, while Germany uses the *Betriebssicherheitsverordnungen*. Any product that meets the standards of national legislation is therefore also compliant with the underlying European Directives. Such products may be traded freely within the European Economic Area (EEA). Products that are traded between the Member States need not be imported again.

European Product Directives are structured around a series of essential requirements. Those requirements apply to such matters as safe design and instructions for the user, and are laid down in Annex I to the Product Directive. The Directive states that a manufacturer must prove for each of those essential requirements that the product meets the safety level specified by the Directive. The safety levels are given shape in standards, to which all European Member States subscribe, making them harmonised European standards. Those standards are updated regularly, and as such are deemed to represent the latest state of the art. If a manufacturer uses the harmonised standards as they apply at the time, it may be assumed, the European Commission believes, that the product meets the requirements laid down in the Directive. Though the standards are not obligatory, applying them helps manufacturers demonstrate that they meet the safety level specified in the essential requirements. Pursuant to one of the essential requirements, manufacturers are obliged to carry out a risk assessment, involving mapping out risks attached to the product and applying risk-reducing measures (control measures) when designing and manufacturing the product.

The manufacturer must be able to prove that the product meets the safety standards laid down in the Directive, based on a Technical Construction File (TCF). That file should specify what Directives and what essential requirements apply, what risk-reducing measures were taken and what standards and technical specifications were applied. By displaying the CE mark on the product, the manufacturer states that in its opinion the product meets the requirements laid down in the European Product Directives that apply to the product (compared with international standards and national legislation). The manufacturer may then trade the product freely within the European Economic Area. The product must have an EC declaration of conformity, in which the manufacturer declares that the product is compliant with the Directives.

Tower cranes and the parts making them up are governed by four European Product Directives: the Machinery Directive, the Electromagnetic Compatibility (EMC) Directive, the Low Voltage Directive and the Noise Directive. Here, too, the manufacturer may complete the CE marking process itself without involving an inspection agency. Pursuant to the Machinery Directive, a European harmonised standard has been defined for the electrical parts on machinery[1]. The Low Voltage Directive does not specify any additional requirements on top of that standard, and as such is disregarded for purposes of this assessment framework. Similarly, the Noise Directive[2] applies to tower cranes, yet is not included in the assessment framework. The measures taken to prevent noise emission had no bearing on the collapse of the tower crane.

3.2.2 The Machinery Directive

The definitions concerning the Machinery Directive's scope indicate that that Directive applies to tower cranes. Annex I to the Machinery Directive lists the essential requirements, grouped into paragraphs. Paragraph 1 lists requirements for the design and construction of machinery. Besides paragraph 1, paragraph 4 also applies to tower cranes. Paragraph 4 lists additional essential requirements for hoisting and lifting operations. Both of those paragraphs and the relevant requirements are included in Annex E. The essential requirements are phrased as questions. Examples of questions that correspond to the investigation discussed in this report are[3]:

"*Have all risks been eliminated or reduced as far as possible in the design?*"
"*Have the necessary protective measures been taken in relation to risks that cannot be eliminated?*"
"*Have the control systems been designed and constructed in such a way that they can withstand the rigours of normal use and external factors?*"
"*Can the parts withstand all possible loads under all conditions and in all possible configurations?*"
"*Were the dynamic tests carried out under unfavourable conditions (in terms of speed and combined movements)?*"

Annex IV to the Machinery Directive provides an overview of products for which the inspection services of a *Notified Body* or *NoBo* are required. Those products include handheld circular saws, chain saws and rubbish collection trucks, for example, but not tower cranes. As such, manufacturers of tower cranes may declare independently whether their products are compliant with the Directive.

3.2.3 The Electromagnetic Compatibility Directive

The purpose of the Electromagnetic Compatibility Directive (EMC Directive) is to prevent appliances from affecting one another as a result of electromagnetic malfunctions. Two matters are important in this respect. Appliances and installations must be protected against outside interference, and they may not affect the proper operation of appliances. Electromagnetic disturbances can influence the *safe* operation of appliances. The Dutch Safety Board uses the Directive as its assessment framework for investigating the possibility of influence on the operation of the tower crane as a result of electromagnetic malfunctions.

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[1] EN-IEC 60204-1: electrical equipment of machines
[2] European Noise Directive 2000/14/EC
[3] Machinery Directive Annex I §1 1.1.2.b1.; 1.1.2.b2; §1 1.2.1.a; §4 1.2.3.a1; §4 1.2.3.f

3.3 DUTCH LAWS AND REGULATIONS

3.3.1 General

The European Product Directives have been incorporated into Dutch law in the Commodities Act (*Warenwet*) and the underlying Commodities Act Decrees (*Warenwetbesluiten*). It is the manufacturer's responsibility to ensure that the product is compliant with the Dutch Decrees. The tower crane in this investigation was sold in Germany, based on the *Betriebssicherheits-verordnungen*. This involved the new construction and sale of a product.

Some of the laws and regulations governing the use are also based on a European Directive, the Use of Work Equipment Directive. That Directive does not concern product safety and manufacturers but work safety, i.e. working conditions. The Directive lays down certain minimum safety requirements for work equipment, including machinery, to protect workers. This includes the maintenance and inspection of the work equipment. It is the responsibility of the *employer* to ensure that work is carried out in accordance with the Directive, which applies to the operational phase of products. In the Netherlands, the Use of Work Equipment Directive has been incorporated into the Working Conditions Decree (*Arbeidsomstandighedenbesluit*) pursuant to the Working Conditions Act (*Arbeidsomstandighedenwet*).

3.3.2 Commodities Act (Machinery) Decree

Section 2 of the Commodities Act (Machinery) Decree (*Warenwetbesluit Machines*) states that it is prohibited "*to trade or to use machinery or safety components that are not compliant with the manufacturing requirements imposed in or pursuant to this Decree.*" Section 3 states that machinery must be safe and must meet the essential requirements set out in Annex I to the Machinery Directive (see Annex C). Pursuant to Section 4, machinery must bear a CE mark and have an EC declaration of conformity. These rules apply to newly built machinery.

For the operational phase, Section 6d states specifically for tower cranes that the crane must be inspected at least once every year by an expert natural person, legal entity or institution. Once every two years, the crane must be inspected by an agency designated by the Ministry of Social Affairs and Employment, the first such inspection taking place two years after it is first put into operation. Essentially this means that the crane must be inspected every year, alternately by an expert and by a designated inspection agency. The results of the inspection must be kept in the crane's vicinity, in the crane log (Section 6f). The Commodities Act (Machinery) Regulations (*Warenwetregeling Machines*), which provide more concrete details to the Commodities Act Decree, specifies what inspection requirements apply to tower cranes, referring to the inspection requirements described in the certification schedule of the Foundation for the Supervision of the Certification of Vertical Transport TCVT.[1]

3.3.3 Working conditions laws

The Netherlands Working Conditions Act is a framework act that defines the direction that employers and employees should take in handling safety, health and wellbeing. Further details to that framework act are laid down in the Working Conditions Decree. Title 5 of Chapter 2, entitled "*Construction process*", and Chapter 7, entitled "*Work equipment*", have specific bearing on this investigation.

Chapter 7 of the Working Conditions Decree refers to the Commodities Act Decrees, and states that a piece of work equipment is deemed to meet the requirements that the Working Conditions Decree sets for work equipment if it bears a CE mark and is accompanied by an EC declaration of conformity (Section 7.2).

Chapter 7 of the Working Conditions Decree also lays down requirements for inspections: "*A piece of work equipment whose safety depends on the manner in which it is installed must be inspected*

[1] certification schedule with identification code TCVT W3-11/07-148

to determine whether it has been installed in the correct manner and whether it works properly and safely, after it has been installed but before it is put into operation for the first time."[1] Work equipment must be inspected again if it is reinstalled (at a different location) or if the work equipment has been modified. Proof of the inspections must be kept at the place of work (with the machinery). For cranes, those documents are included in the crane log. Inspections must be carried out by an expert natural person, legal entity or institution.

Pursuant to the Working Conditions Decree, the use of hoisting or lifting equipment is subject to a series of rules. Requirements are made of the crane operator's expertise and the way in which the hoisting is organised, to ensure that no persons find themselves under a hoisted load.

What is typical of the Working Conditions Act is the part assigned to the *employer* in ensuring proper working conditions (the health and safety of workers). Section 16(8) of the Working Conditions Act allows possibilities to transfer the obligation to comply with rules to other parties. Chapter 2, Title 5 of the Working Conditions Decree on building sites places that responsibility, during the work phase, with the party carrying out the work. That party must appoint a coordinator for the work phase, who is charged with ensuring the effective implementation of measures to protect the health and safety of workers. The principal must ensure that a Health & Safety Plan (H&S plan) is prepared, containing, among other details, a Risk Identification and Evaluation (RI&E) and measures arising from that RI&E.

3.3.4 Planning Application (Submission Requirements) Decree

Care for people outside the construction site is not included in working conditions legislation, but instead is governed by building regulations. The Planning Application (Submission Requirements) Decree (*Besluit Indieningsvereisten Aanvraag Bouwvergunning*), which is based on the Housing Act (*Woningwet*), demands that a building safety plan be submitted for this matter. The municipal authorities may include the building safety plan in the conditions for the permit. "*The building safety plan only concerns the safety of the road, works situated in the road, road users, adjacent construction work, open land and sites and their users*".[2]

3.4 INDUSTRY STANDARDS

The Dutch Safety Board did not identify any industry guidelines that specifically address risks or safety with respect to the design and construction of tower cranes. The parties involved in this investigation are minor, and have not formalised any internal company guidelines in writing. No new aspects are added to this investigation's assessment framework in this context.

The Foundation for the Supervision of the Certification of Vertical Transport (TCVT) draws up inspection requirements, in the form of certification schedules for the professional expertise of crane operators and the state of repair of cranes. The Commodities Act (Machinery) Regulations refers to those requirements. The Foundation's board is made up of representatives from employer and employee organisations, principals and staff working for the Foundation. The work groups also include representatives from suppliers, the government and inspection agencies. TCVT has drawn up a certification schedule for periodic inspections of cranes.[3] That schedule consists of an assessment and test form and a set of instructions. The certification schedule is enclosed to this report as Appendix E.

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[1] Working Conditions Decree, Chapter 7, Title 2, Section 7.4a. "*Inspections*"
[2] Planning Application (Submission Requirements) Decree § 3.2.6
[3] Certification schedule for TCVT Certificate of Approval, Periodic Inspection of Crane W3-11/07148, 11 July 2007, presented by the Foundation for the Supervision of the Certification (TCVT)

3.5 Safety management

Past experience has shown that the structure and implementation of the safety management system plays a crucial part in managing and continually improving safety. This is the same for all organisations, both private and public, that are involved either actively or indirectly in activities that may give rise to potential hazards for people in the Netherlands.

As a rule, the way in which an organisation gives shape to its own responsibility with respect to safety can be tested and approached from various angles. As such, no universal handbook exists that can be used in every situation. That is why the Dutch Safety Board has selected five safety issues on its own, to give an impression of what aspects may affect the situation to a greater or lesser degree. The issues selected by the Board are based on national and international laws and regulations, and on a large number of generally accepted and implemented standards.

The following issues are distinguished:

Information about risks as the basis for the safety plan
The point of departure for achieving the requisite level of safety is to examine the system and then map out the accompanying risks.

This is taken as the basis for determining what hazards need to be controlled and what preventative and repressive measures are needed to achieve that.

Demonstrable and realistic safety plan
Preventing and controlling undesirable events requires that a realistic and practicable safety policy be determined, which includes the relevant assumptions. That safety plan must be adopted and guided at management level. The safety plan is based on:
- relevant current laws and regulations,
- standards, guidelines and best practices that are available in the industry, and
- the organisation's own information and experiences and the safety targets defined specifically for the organisation.

Implementation and enforcement of the safety plan
The safety plan is implemented and enforced and the risks identified are controlled using the following methods:
- A description of the way in which the safety plan adopted is put into practice, focusing on the concrete targets, plans and resulting preventative and repressive measures.
- A transparent, clear-cut and universally accessible allocation of responsibilities on the workfloor in terms of implementing and enforcing safety plans and measures.
- A clear record of the requisite deployment of personnel and expertise for the various tasks.
- Clear and active central coordination of safety activities.

Improvement of the safety plan
The safety plan must be improved continually, using the following methods:
- Periodically, and at least each time the assumptions undergo any change, proactively performing risk analyses and other analyses, observations, inspections and audits.
- Introducing a reactive system of monitoring and investigating incidents, near-accidents and accidents, including an expert analysis.

Based on the results, evaluations are carried out and if necessary management modifies the safety plan. In addition, possibilities for improvement are brought to light that can be used as active focal points for management.

Management control, involvement and communication
The management of the parties/organisation involved has the following obligations:
- *Internally*, to ensure that the expectations for the safety ambition are clear and realistic, that the work is carried out in a climate of continually improving safety by leading by example, and finally that sufficient people and resources are available.
- *Externally*, to communicate clearly about the general approach, the way in which that approach is tested, the procedures for any non-standard situations etc., based on clear-cut and formalised agreements with the relevant parties.

The Dutch Safety Board is aware that the review of the way in which organisations give shape to their own responsibility for safety depends on the organisations in question. Aspects such as the nature of the organisation, for example, or its size may be relevant factors and as such should be taken into account in the review. Although the way in which the Board forms its opinion may differ from case to case, the way of thinking remains the same.

4 THE PARTIES INVOLVED AND THEIR RESPONSIBILITIES

4.1 INTRODUCTION

This chapter describes the parties involved in their respective contexts and in relation to one another. The purpose of this description is to establish the responsibilities of the parties involved in terms of safety, as part of the investigation into the collapse of the tower crane. For purposes of the investigation, the Dutch Safety Board distinguishes between three groups of actors.

The first group of actors is the network around the construction site where the crane collapsed and the construction process (see Figure 8, blue part). The contracting firm hired the crane. The contractor worked for a property developer. That property developer commissioned the design from an architect (not included in the diagram in Figure 8). Similarly, it was the property developer that applied for a building permit from the municipal authorities. The municipal Building and Housing Supervision Department (BWT) reviewed the application for the permit and monitored the compliance with that permit. The VROM Inspectorate monitors the implementation of laws and regulations by the municipal authorities (Building and Housing Supervision Department), using inspection programmes with random checks. The final party involved is the staffing agency that supplied the crane operators for working in the tower crane at the construction site. Those operators were hired by the crane's owner.

The second group of actors that the Dutch Safety Board distinguishes concerns the management and maintenance of the tower crane (see Figure 8, orange part). The central actor in this network is the Dutch owner renting out the crane. An expert and specially designated agency inspects the crane periodically and each time it is re-erected, at the owner's instructions. The agency is designated by the Minister of Social Affairs and Employment. When designating such agencies, the Minister requests for that agency's accreditation by the Dutch Accreditation Council (not included in Figure 8). Certification schedules for the operator's professional skill and the state of repair of tower cranes are prepared by the Foundation for the Supervision of the Certification of Vertical Transport TCVT. The board of that foundation and its working groups are made up of the various parties on the market and the government. Those certification schedules are mentioned in legislation (see Chapter 3 and Appendix E).

The Labour Inspectorate is responsible for monitoring compliance with laws and regulations relating to maintenance and inspections, requirements for crane operators and rules for hoisting. The Labour Inspectorate also monitors compliance with the H&S plan and the care for the health and safety of everyone on the building site (Figure 8, orange part).

The third group of actors centres on the tower crane's manufacturer (see Figure 8, green part). That manufacturer is based in Germany, and is required to comply with the Directives of the European Commission as incorporated into German law. This group is not really related to the other two groups, the sole link being the buyers.

4.2 THE PARTIES INVOLVED

The contractor

The contracting firm in question is a small young firm with a small number of construction projects. The contractor carries out construction work for the property developer and the architect. The contractor hires subcontractors to execute projects. The contractor's own work consists primarily of management.

The contractor hired a tower crane from a rental firm for the work. The contractor organises the work involving hoisting, and gives the crane operator his instructions. In this context, the contractor is responsible for the safety and working conditions of everyone at the construction site (pursuant to the Netherlands Working Conditions Act), including the crane operator.

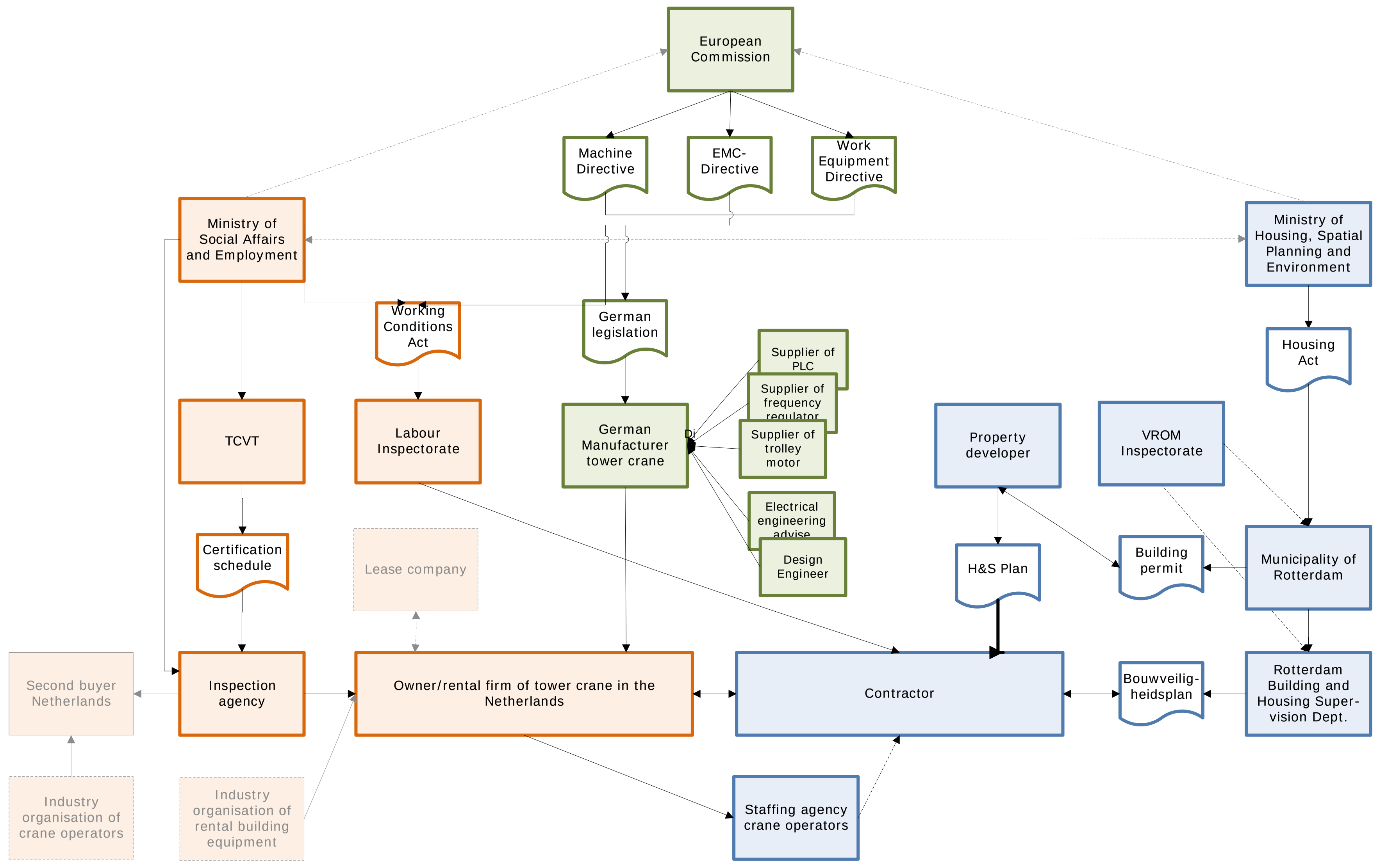

Figure 8: Interconnections between parties involved, within the context of regulations and standards

The risks of the construction process for workers and third parties outside the construction site have to be mapped out beforehand. Measures aimed at reducing those risks are described in the Health & Safety Plan (pursuant to the Working Conditions Act) and the building safety plan (pursuant to the Housing Act), which are both drawn up by the contractor at the property developer's instructions. The contractor is responsible for everything that happens at the construction site. He is responsible for the workers' health and safety and for all the work at the building site that affects or may affect people in the vicinity of the site who have no connection to the work on the site itself.

The property developer

The property developer finances the construction project and is the principal for the architect and the contractor. He awarded the project to the contractor in a private tender based on a calculation of the price. The property developer is responsible for appointing a coordinator who ensures that a Health & Safety Plan is drawn up and complied with during the work phase. In this case that was the contractor. The property developer also ensures that the additional requirements of the building permit are met. This includes, at the minimum, the submission of a building safety plan.

The Building Control Department of the Municipality of Rotterdam

The construction site at Prinsenlaan is situated in the Municipality of Rotterdam. The Municipality of Rotterdam is responsible for issuing building permits. Besides the conditions for the permit for the building, this also includes requirements for the construction process and safety at the construction site. One part of the permit requirements is the building safety plan, in which the contractor must explain how he intends to guarantee the safety of third parties outside the construction site during the construction process. The municipal Building and Housing Supervision Department monitors the issuance of the permits and compliance with the permit requirements.

The crane operator's staffing agency

The tower crane's owner/rental firm had an arrangement with a staffing agency. The agency provides a crane operator for the period specified and ensures continuity. On site, the operator reports to the contractor's foreman, who has the key or keys to the crane. The operator receives his instructions from the foreman.

Pursuant to the Netherlands Working Conditions Act, the staffing agency is required to identify the working conditions and the risks to which its employee is exposed, for which they must contact their client.

The tower crane's owner/rental firm

The owner that rented out the tower crane is a Dutch-based firm. Besides hoisting and lifting equipment, this firm only rents out tower cranes from the manufacturer (see next page). Older rental equipment not built by the manufacturer is being phased out over approximately three years. The rental firm's target is to have a fleet of cranes built entirely by the manufacturer by the end of that period. The owner does not rent out any other brands of tower cranes.

The owner rents out tower cranes, with an operator if the client so wishes. That was the case in Rotterdam. Those operators are always hired from the same staffing agency. The owner shares responsibility with the staffing agency for the continuity of this service.

The owner advises clients on what crane can best be used, based on the expected height, span and weight. The owner erects the crane and arranges an inspection once the crane is in place. It arranges maintenance and is the first point of contact in the case of malfunctions. The owner employs several repair mechanics in case of malfunctions.

The owner erects the cranes itself and is responsible for ensuring that that work is done properly. It is also required to have the crane inspected. Similarly, the owner is responsible for advising properly about the use and possibilities of its cranes. On the matter of arranging operators, the owner shares the responsibility for providing an operator with the necessary papers and for informing the staffing agency of the risks to which the operator will be exposed.

The inspection agency

The inspection agency is an independent accredited firm, designated by the Ministry of Social Affairs and Employment to carry out bi-annual and erection inspections of tower cranes and other equipment. The firm uses the certification schedules of TCVT for those inspections. Both of the inspections described in this report were carried out by the same inspection agency, at the instructions of the crane's owner. The reports of those inspections were included in the crane log.

Foundation for the Supervision of the Certification of Vertical Transport TCVT

The Foundation for the Supervision of the Certification of Vertical Transport (TCVT) details the certification requirements for crane operators, hoisting equipment and cranes at the request of the Ministry of Social Affairs and Employment. The Foundation is made up of representatives from the industry and a supervisory unit. The certification schedules are tested by the Ministry of Social Affairs and Employment.

Labour Inspectorate

The Labour Inspectorate monitors compliance with working conditions legislation. This involves the supervision of obligations in respect of protecting the health and safety of workers. One of the ways in which the Labour Inspectorate carries out this task is through inspection programmes for specific matters or issues and based on reports of industrial accidents or complaints.

Within the framework of its task, the Labour Inspectorate focuses on risks at construction sites rather than on off-site risks. In connection with cranes, the Labour Inspectorate concentrates on how such equipment is used. The Labour Inspectorate also monitors the presence of a crane log, a CE mark, an EC declaration of conformity and a Dutch-language user manual. In addition, the Labour Inspectorate looks out for risk factors such as the range of rotation of cranes, falling objects, the proper maintenance of safety features, expert operation and periodic inspections.

The tower crane's manufacturer

The manufacturer has been constructing its own brand of tower cranes since 2003. The tower crane in Rotterdam was also one of its own brand. Prior to 2003, the manufacturer only rented out tower cranes. When its supplier stopped, the current manufacturer started building tower cranes of its own to rent out. Following requests from clients, the manufacturer also started selling cranes. The cranes that the manufacturer now builds can be erected using the same mast sections as the cranes that the manufacturer rented out previously. The manufacturer still rents out those mast sections alongside new mast sections. The manufacturer is domiciled in Germany and works through agents in other European countries. The agent in the Netherlands is the owner/rental firm also discussed in this investigation.

The manufacturer uses the services of an independent design engineer to design the cranes and calculate their configurations. It also engages an independent consultant for the electronic parts of the crane. Early in 2009, a consultancy firm was engaged to replace that consultant, who will be retiring shortly. The electronic components are purchased and assembled by the manufacturer.

The manufacturer has rented out several cranes to the Dutch rental firm. The cranes in question are of the brand that the manufacturer previously rented out itself. It sells its own brand to the Dutch rental firm. This only concerns the cranes, i.e. everything from the tower ring up. The manufacturer rents out the mast sections to the Dutch rental firm. The reason for this is that, depending on the type of work for which the crane is used, tower cranes have different configurations. The crane remains the same: the variable elements are the length of the jib, the mast and the base (rolling undercarriage, undercarriage or poured foundation).

The manufacturer performs the repairs and maintenance work to the cranes for the Dutch rental firm from Germany.

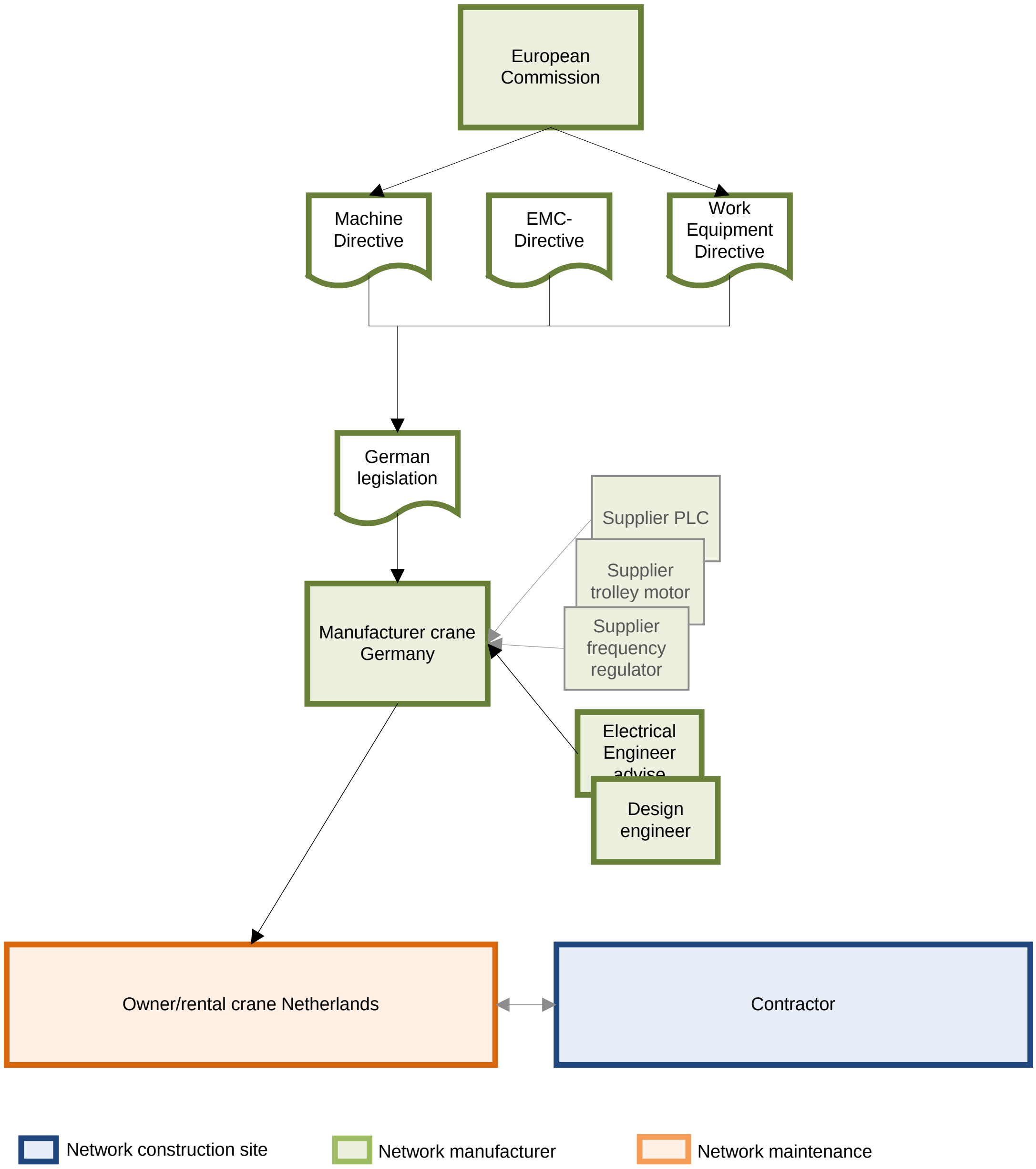

Figure 9 – Manufacturer in Germany connected only to the Dutch network through its customer

To be permitted to sell the crane in Europe, the manufacturer must be compliant with the European Directives as incorporated into the laws of the individual Member States. The manufacturer must be able to demonstrate that, in its own opinion, the product meets the requirements of the Directives, using the de CE mark. This means that the manufacturer judges for itself whether it is compliant with the regulations and may use the mark. The German manufacturer has no contacts with Dutch supervisory authorities or certification institutions (see Figure 9).

It is the responsibility of the crane manufacturer to sell a reliable product that is compliant with the applicable Directives. The proper working of the crane applies to the composite of parts in all configurations to which the manufacturer attaches its approval. The manufacturer has the final responsibility for the product created. In light of the services that the manufacturer provides, it is also responsible for the reliability of various non-standard configurations and for maintenance.

The design engineer of the tower crane

The design engineer of the tower crane in question is an independent consultant, working as the manufacturer's regular design engineer. The design engineer designs cranes and, at the manufacturer's instructions, makes calculations for configurations for the Dutch owner/rental firm if those configurations deviate from the standard configurations described in the crane's user manual. The design engineer advises the manufacturer. He is responsible for the reliability of the advice that he provides to the manufacturer.

The electrical engineering consultant

The electrical engineering consultant also worked for the manufacturer as an independent consultant. He offered advice about the standard configuration for the electronics and the switching programs for the various types of cranes. The electrical engineering consultant advised the manufacturer, but did not have final responsibility for the product created. He too was responsible for the reliability of the advice that he provided to the manufacturer.

Together with the manufacturer, the electrical engineering consultant has selected a firm and shown it the procedures; that firm has since replaced him because he has reached retirement age.

4.3 DIRECT CAUSE OF THE COLLAPSE OF THE TOWER CRANE

4.3.1 Introduction

In order to determine the direct cause, various partial investigations had to be carried out. Chapter 2 sets out the general outlines of the details arising from those investigations. In this chapter, those details are combined.

The Dutch Safety Board distinguished three scenarios for the accident. The first scenario is that the tower crane was used in a way that fell outside the conditions for use and parameters defined for the crane. The Dutch Safety Board found nothing pointing in that direction. This is discussed in section 5.1.2. The second scenario for the accident is that the crane collapsed as a result of faults or weaknesses in the steel construction. This scenario is also rejected by the Dutch Safety Board as the basic cause, since the investigation into the steel construction revealed nothing out of the ordinary. However, the sections dealing with the collapse of the steel construction and the models made of that construction reveal that the collapse resulted from an overload. This is the third scenario. The Dutch Safety Board considers this scenario to be the only probable one. This scenario is based on four partial scenarios, which are explained in section 5.2.

4.3.2 Scenario one: operational parameters exceeded

The principle of a trolley tower crane is based on balance. The load on the hook is balanced by the counterweight on the rear jib. The crane's strength and rigidity add some margin to the balance, allowing the front jib to carry an extra load on top of its own weight. The leverage caused by the weight on the jib means that the maximum weight that can be hoisted close to the mast cannot be moved out to the end of the jib. The moment at which the balance is disturbed is reached at a smaller load the further along the jib from the mast. This means that the maximum weight that can be hoisted is not the same for each radius. That is why, to monitor the balance, it is important to know what weight is hanging from the hook and at what distance on the jib the load is hanging. This load moment is used to control the crane's safety.

The Load Moment Security (LMS) system is an important instrument for achieving this. This security system monitors the crane's balance for the operator. The LMS works on the principle that it will not permit a particular weight to be moved to or hoisted at too great a radius. The LMS does this by intervening in the operation of the crane and preventing a command to hoist or move out a load from being carried out, or, if the movement has already started, stopping that movement. As such, the LMS limits the crane's functional scope to the maximum load for each radius. For example, for the tower crane in Rotterdam the maximum load permitted at a radius of 3 metres[1] to a radius of 23 metres was 16 tonnes, at a radius of 40 metres 8.7 tonnes and at the maximum radius of 50 metres 6.7 tonnes. Failure of this security system presents a major risk to the crane's balance. If the balance is lost, the crane will, as a rule, collapse.

The LMS is vital for the security of the crane's balance. The investigation into the collapse of the tower crane at Prinsenlaan in Rotterdam revealed that the key-operated switch in the switch box at the back of the rear jib was set to a normal operational mode. This means that the LMS had not been deactivated. If it had been, the radius would not have been limited by the LMS. Similarly, it can be inferred from the last events before the crane collapsed that the LMS was working. The reconstruction of the events showed that the operator first tried to swing the load around the building. That did not work. The load was then hoisted over the building. Based on these details, the Dutch Safety Board considers it safe to assume that the LMS was triggered, and worked properly, immediately before the accident.

At the moment of the accident, the balcony slab on the hook was hanging immediately in front of the point where it was to be placed. The total load of almost 13 tonnes was suspended at a span of around 27 metres. It was not being hoisted, lowered or moved in or out rapidly. The load chart shows that this weight, in that position, was between the maximum load moment and 90% of the

[1] The minimum distance from the heart of the trolley to the mast, i.e. the minimum radius, is 3 metres.

maximum load moment. If everything was working as it should, an initial software security feature would have been activated within these margins of the load chart. According to the crane's design, the operator should have received a warning in the form of a red bar on the monitor and an acoustic signal. That signal indicates that the load moment has exceeded 90% of the maximum. When the load was moved out, the speed of that movement will have been reduced, preventing an abrupt stop when the maximum load moment was reached. Based on the events immediately prior to the crane's collapse, it can be inferred that this feature was indeed working in that manner. This means that the work was being carried out within the operational parameters, though close to the limits of those parameters. Based on the findings described above, the possibility of failure based on operational actions can be excluded.

4.3.3 Scenario two: collapse of the steel construction

The tower crane's mast was bent, broken and torn loose (see Figure 10). The second obvious scenario based on the damage profile is that the steel construction of the mast did not match the design specifications at the moment of the accident. The analysis of this scenario required a destructive investigation. The Dutch Safety Board coordinated with the Public Prosecution Service[1] to have this investigation carried out by the Schielab laboratory in Rotterdam.

Schielab investigated the material specifications and the fractures (see Annex C). Schielab took samples from the material surrounding the fractures and subjected those samples to chemical analyses and tensile tests. These revealed that the material used matched the specifications defined. The fractures were found to be “ductile fractures”. Schielab was able to determine this using microscopic investigation and based on the fact that warping and a reduction in the thickness of the sides were visible at and near the fractures. The fractures were caused by overloading. This led Schielab to conclude that the crane's failure was not the result of material defects. The Dutch Safety Board endorses that conclusion.

Figure 10 – Bent mast sections

Figure 11 – Broken connecting part (Photograph: Aboma Keboma).

Figure 12 – Buckled tower leg

The profile of the damage to the mast shows a series of constituent events. The first is that the four tower legs all tore loose at the same place in a mast section. The second is that the mast sections were warped, causing the tower legs, which are normally positioned in a square, to land almost in a flat plane (see Figure 10). The third is that the connecting plug in the left rear tower leg broke (see Figure 11).

It can be determined based on the damage profile that the last of these events did not occur first. The fracture surrounding the plug (the mortise and tenon joint) in the right rear tower leg is bent. Damage is also visible where the tower leg that was still attached left a clear impression. This indicates that the tower leg first bent sharply before breaking at the joint around the plug.

The fractures in the third mast section above the transitional section – where the mast was torn loose at all four tower legs - are fractures caused by tension strain. A simultaneous tension strain

[1] As required by the Dutch Safety Board Act (*Wet op de Onderzoeksraad*) and the agreement with the Public Prosecution Service.

on all four tower legs cannot be explained if the tower is upright, since the crane's weight must always be pressing down on one or more of the tower legs. If that was not the case, that mast section was therefore no longer in upright position. The materials investigation therefore also demonstrates that the upper part of the tower tore loose after the tower bent, meaning that that tearing was consequential damage.

The significantly deformed and bent mast section presents the most probably starting event in the tower crane's collapse. A buckle is visible in the right front tower leg, at approximately one metre from the bottom of the first lighter mast section above the transitional section (see Figure 12). That tower leg felt the greatest load strain, while the greatest tension strain was on the right rear tower leg. A heavy strain caused the mast of the crane to bend, as it were pressing down the front (the side of the jib) and stretching down the rear (the side of the rear jib). The front right tower leg buckled under that strain, as a result of which the crane bent over. The left rear tower leg tore loose because of tension strain, as it is called. The two other tower legs served as hinges.

4.3.4 Scenario three: overload

The inference of these events from the damage profile is confirmed by simulations carried out by FEMTO Engineering, using a computer model of the crane. In various simulations, such as gradually increasing a downward force at one point along the jib, similar to a load on the hook, the model each time displays the failure mode that occurred in reality.

The model shows that the jib of the collapsed crane, with no load at a span of 27 metres, is suspended 0.5 degrees above level (see Figure 13). In the simulation, the jib bent 2.1 degrees below level if a 13-tonne load was hanging from the hook at a radius of 27 metres (see Figure 14). These measurements were taking with a load that was hanging still (static load). If the load swings or the hoist cable comes to an abrupt stop while lifting or lowering and the crane springs out (dynamic load), the bend will be greater. If the trolley moves out to a radius of 50 metres, the bend calculated in the model is 5.2 degrees below level. The manufacturer's calculations are based on 0.6 degrees below level, and uses 1 degree below level for the maximum bend permitted in the jib. The models created by FEMTO imply that the construction's flexibility is greater than was assumed based on the calculations.

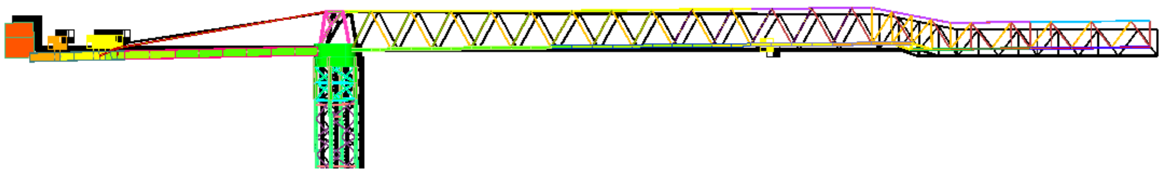

Figure 13 - Model of the tower crane: no load 0.5 degrees above level (source: FEMTO Engineering)

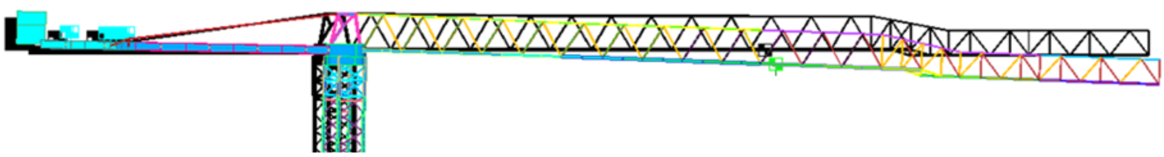

Figure 14 - Model of the tower crane: 13-tonne load 2.1 degrees below level (source: FEMTO Engineering)

The bending of the jib below level affects the trolley, causing it to run along a slope and, owing to gravity, to start moving sooner. The conclusion of the Dutch Safety Board is that once the trolley starts to move along the jib out of control, with a permitted (maximum) load, the increasing bend will mean that it will keep accelerating down the slope until it reaches the end of the jib. If the crane is overloaded, the model predicts a scenario that is similar to the reconstruction of the crane's collapse. The front right tower leg buckles, while the tensile stress on the left rear tower leg at the same time is so great that it almost begins to warp. Although no visible damage occurred in practice, in FEMTO's calculations the same happened with the tension rod linking the masthead and the jib's upper bar. The collapse of the crane requires a larger static load (hanging still) than the 13 tonnes it was carrying at the time of the accident. As such, it is safe to assume that other forces played a role in the crane's collapse.

4.3.5 Partial conclusion

Based on the events described above, the Dutch Safety Board finds that the crane collapsed as a result of an overload. However, this does not serve to explain how the crane came to be fatally overloaded.

4.4 PARTIAL SCENARIOS FOR THE OUTWARD MOVEMENT OF THE TROLLEY

4.4.1 Introduction

Based on the investigation into the steel construction, the Dutch Safety Board determined that the tower crane in Rotterdam collapsed as a result of an overload, caused by other forces. One of those other external forces that may cause an overload is the wind. However, the weather on the day of the accident was calm. Although the moderate southerly wind was blowing across the jib when the crane collapsed, it did not cause the load to move visibly. The wind did not unbalance the crane.

Other forms of forces working on the crane relate to the position and movement of the load hoisted. According to the load chart, the balcony slab with its balancing device, totalling almost 13 tonnes, could be lifted to a radius of 28 metres. The load could have resulted in an overload if the trolley were to move out beyond that distance of 28 metres.

Dynamic forces are also forms of other forces working on the crane. They are forces that occur if the load swings, if the hoist cable comes to an abrupt stop during lifting or lowering or if the trolley comes to an abrupt stop while moving in or out. Finally, forces might be exercised on the hoist cable if the load or the hoist cable were to catch on something.

At the starting position before the accident, the load was in a reasonably static position: it was not being lifted or moved in or out rapidly. The load was hanging virtually still and the hoist cable was hanging loose. From that position, the load was moved away from the mast along the jib, after which an overload situation arose. This can only have happened if the trolley was moved out unintendedly. As such, the Dutch Safety Board considers the trolley's unintended movement beyond the maximum load moment to be the primary cause for the collapse of the tower crane. This chapter addresses the possible causes for that unintended movement of the trolley (Scenario 3 ‘overload’ in section 5.1.4) and the way in which that event could cause an overload of such magnitude that the crane collapsed.

4.4.2 Scenarios for the unintended movement of the trolley

A number of scenarios can be distinguished in which the trolley unintendedly moved out further. The common factor uniting those scenarios is that energy is needed to move the trolley out. That energy could be generated by the trolley's propulsion or be caused by gravity. The crane in Rotterdam had a load of almost 13 tonnes on its hook, and its jib sloped down at an angle of 2 degrees in the direction of the point of the jib. If the trolley was not held in place, it could move out to the end of the jib of its own accord.

Several crane parts are important in order to move the trolley or keep it in place. The trolley motor turns the drum around which the trolley cable runs. This causes the trolley cable to move and moves the trolley along the jib, or holds it in place. The trolley is also slowed by the motor. The locking brake on the trolley motor is intended for holding the trolley in place if the trolley motor is not activated. The frequency regulator of the trolley motor controls the locking brake and the motor, as well as determining the motor's rotation direction. The frequency regulator in turn is controlled by the *Programmable Logic Controller*.

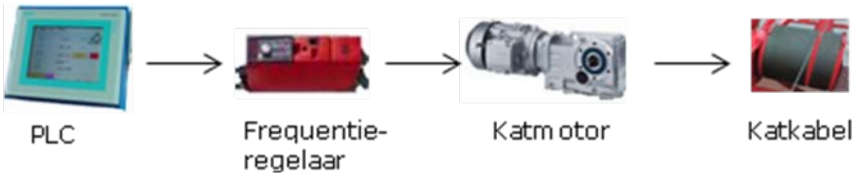

Figure 15 – Schematic representation of the crane parts in the failure scenarios

These parts were incorporated into the design to act as a single unit. Within that unit, each part has a separate function. If one part does not do its work properly, it is said to have failed. Failure of a part may cause the whole unit's functioning to fail. Failure does not necessarily mean that something has broken down. The frequency regulator fails if it does not provide sufficient power, even if it is not malfunctioning. For example, the wrong frequency regulator may have been installed, within insufficient power. The cause of the failure is then that an incorrect frequency regulator was installed.

A finite number of scenarios can be posited for the movement of the trolley, in which failure of the various crane parts at different moments and in a different sequence may play a role. The sections below describe the failure mechanisms of those crane parts.

4.4.3 Failure of the Programmable Logic Controller (PLC) and cable connections

The Dutch Safety Board considers the programming of a PLC to be critical to safety. The PLC is where the conditions are determined that must be met before operational actions can be carried out safely. Errors in the definition of the conditions may have a great impact. This is particularly the case with the LMS module: a load may not be too heavy to hoist, and once a load is in the air it may not be moved out too far. Monitoring the operational conditions of ‘weight’ and ‘span’ in the load chart is an important factor in the ‘hoist’ and ‘move out’ commands. Those actions increase the load on the crane. The commands of ‘lower’ and ‘move in’ involve fewer risks, since they decrease the load on the crane. As a rule, the LMS need not intervene in those actions. In the PLC's logic (the description of the correct sequence of cause and effect), the LMS module is triggered with the high-risk actions of hoisting and moving out, but not with the command to move the trolley in.

If an error were to occur in the move-in command, and the trolley were to inadvertently move out, according to the applicable standards the LMS need not be triggered, nor do the conditions indicate that it should[1]. As such, the LMS will not intervene based on that event. It should be noted that the PLC includes a safety feature for the direction in which the trolley motor turns. For these purposes, the position of the joystick is compared with the positional indicators. However, this is not a conditional safety feature that prevents movement, but a monitoring safety feature that detects a wrong movement, i.e. one that has already commenced. The investigation into the PLC's settings showed that detection of a wrong direction triggers an alarm on the operator's monitor, but not an action. An advisable action might be that the motor is turned off and the brake activated, for example.

Several elements of the PLC's controls were investigated based on the findings in the investigation into electromagnetic disturbances that Dare Consultancy performed at the request of the Dutch Safety Board. Dare's findings reveal that the crane fell short of the prevailing EMC standards in several respects. Too much electromagnetic radiation was generated and the crane did not have sufficient protection against outside electromagnetic radiation. This also means that crane components could influence one another. The absence of proper protection may have been caused by the lack of sufficient plug connections, even if properly insulated cables were used.

The crane's power cables could have affected the crane's own data cables. Similarly, the GSM antenna, which before the investigation the manufacturer always placed in the switch box, could also have caused interference. If the GSM antenna's reception is limited because it has been placed in the cabinet, it will perform a ‘search’ by transmitting at a greater capacity. After the Labour

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[1] Based on the philosophy of safety, the controls should be structured in such a manner that a load can in all situations be placed safely on the ground if such should prove necessary – without conditions.

Inspectorate notified the two owners/rental firms in the Netherlands of this fact the manufacturer modified the other cranes accordingly.

During the tests performed by Dare Consultancy, malfunctions occurred as a result of the electromagnetic fields generated. Those malfunctions showed up on the operator's monitor. This means that the malfunction was identified and an alarm generated. However, the important and logical consequence of that alarm, a logical action such as stopping the crane, is not programmed. Despite the error report generated, therefore, the crane remained fully operational. In the opinion of the Dutch Safety Board, this means that the LMS and the PLC fall short of the objectives they should meet. In this test situation, the LMS and the PLC failed based on design criteria, owing to the absence of sufficiently detailed logic rules.[1]

A risk analysis can be performed to determine the moments at which the LMS logic should play a role and the actions that it should trigger. The manufacturer was unable to present such a risk analysis to the Dutch Safety Board.

Alternatively, the system failure could be caused by factors outside the system, for example if a positional indicator or measuring axle transmits incorrect information that matches the conditions. If the information matches the conditions defined, the system will not detect that it is incorrect and will allow both loads to be hoisted and the trolley to be moved out. This interference occurred during the EMC investigation in Amsterdam, where a malfunction caused a smaller weight for the load to be shown on the monitor than was actually hanging on the hook (this ultimately led to the error message described above). As such a moment, unintended events may occur and remain unnoticed, for example the trolley moving out beyond the maximum load moment. The PLC system failed at that moment owing to the lack of sufficient protection against electromagnetic radiation.

Partial conclusions on the failure of the PLC

The Dutch Safety Board identified several failure mechanisms in the programmable control system of the tower crane in Rotterdam. The failure mechanisms described in this section cannot with any certainty be said not to have occurred. Several of them did actually occur when a similar type of crane was tested. The partial conclusions of the Dutch Safety Board are as follows:

- The logic of the PLC is not geared sufficiently towards the possible events, i.e. several error messages do not lead to actions. As such, the security offered by the logic against unintended events such as the trolley moving out is insufficient.
- The data cables and cable bus connections of positional indicators and measuring axles are susceptible to electromagnetic interference, as a result of which incorrect information can be transmitted without the system detecting that. Properly functioning connections are a condition for the operation of the system as a whole.

4.4.4 Failure of the frequency regulator and trolley motor

An important element of the investigation into the unintended outward movement of the trolley is the investigation into normal trolley movements. Those trolley movements are controlled by the frequency regulator and the trolley motor. A number of important factual findings should be noted. The frequency regulator and the motor from the tower crane in Rotterdam matched in terms of power. The frequency regulator responds to the movements of the joystick for moving the trolley in and out, by way of the PLC. Parameter settings in the frequency regulator control such matters as the magnetisation time (the time needed to power up the motor), the rotational speed and the brake trigger time.

Together with the Netherlands Forensic Institute and a representative of the manufacturer of the frequency regulator, Aboma Keboma investigated the settings of the frequency regulator from the collapsed tower crane.[2] According to the representative of the manufacturer of the frequency regulator, several of the parameter settings in the tower crane in Rotterdam were non-standard. The first non-standard setting was the magnetisation time. The setting for the magnetisation time

[1] Based on the reconstruction of the incident, it is reasonable to assume that the LMS was functioning at the time of the incident in Rotterdam.

[2] The Dutch Safety Board was present for this investigation.

comes into play when the motor is triggered, by way of the frequency regulator, to perform an action. An electrical motor works using a spool, which has to magnetise before the motor can supply power. The settings found in the frequency regulator did not allow the motor sufficient time to magnetise. This means that when the motor was triggered it could not supply its maximum power immediately. A second non-standard parameter was that for triggering the locking brake. The brake trigger time was set for 0 seconds, which means that the brake is lifted immediately if the motor is triggered but has not yet built up power. A third non-standard setting was that for the slip coupling parameter. In the crane, this setting did not include a correction to the rotational speed if the motor was under load. As a result, the rotational speed (and therefore the power) would drop if the motor was under load. The correct setting for the parameters for the slip coupling would have compensated for the drop in rotational speed as a result of the increasing load, ensuring that the power would remain level even if the load increased.

It is important for the proper operation of the trolley motor that the parameters of the frequency regulator are set correctly. Certain settings for the parameters contribute to the motor's available torque dropping, for example a short magnetisation time, a low rotational speed or insufficient latitude for the slip coupling preventing the rotational speed from being adjusted if the load on the motor increases. This causes the motor's functionality to diminish.

The drop in the trolley motor's effective power has consequences for the crane's operation. At low rotational speeds, there is a higher risk that the rotation direction of the motor, and therefore the direction of the trolley's movement, is the opposite of the command given[1]. Similarly, with low power and low rotational speeds, the trolley may continue its outward movement once the joystick is returned to the neutral mode. At low rotational speeds with little power, it is also possible that the electrical motor does not respond correctly to an opposing command: if the command for moving out is abruptly changed to the command to move in, the motor might continue to turn in the same direction. It is precisely when the operator wishes to place a load in position, and is hoisting with precision and care, he uses low power levels. The crane in Rotterdam did not have a feature for linking the rotation direction of the trolley winch drum back directly to the frequency regulator. The rotation direction safety system was built into the PLC (the control computer).

The Dutch Safety Board knows of four incidents during the first six months of 2008 in which trolleys moved out unintendedly on the same brand of tower crane, though on three different types. One crane suffered malfunctions on several occasions. In two cases, the trolley moved out unintendedly on the day of the erection inspection, when the LMS was tested with the maximum load. This is an indication that the problem occurs primarily with heavy loads, but still within the normal operational limits. As such, the outward movement of the trolley could have occurred with each type of this brand of crane, even if the user abided by all the manufacturer's instructions. According to the persons involved, power problems in the frequency regulator and the electrical motor were the causes of those incidents.

Stopping a moving trolley or setting a trolley in motion requires much more power than simply holding the trolley in place. According to the calculations made by the frequency regulator's supplier, the combination of the frequency regulator and the trolley on the crane that collapsed in Rotterdam had barely enough power to hold the trolley in place at the angle of the slope found in the simulation. Under such conditions, drawing the trolley with a load up the slope would be impossible. On the crane in Rotterdam, it probably would have been impossible to move the trolley in. It would also have been impossible to stop the trolley once it had started moving with its heavy load. If the operator tried to move it in, as he was asked, his attempts probably had no effect, while the brake was triggered. If the trolley winch lacked sufficient power, that lack may have caused it to run out, in the opposition direction to the rotational direction, after which control of the trolley was lost.

Partial conclusions on the failure of the frequency regulator and the trolley motor

[1] If the voltage from the frequency regulator to the motor is too low or too high, the electricity may pass through the motor in the opposite direction to the intended direction. The motor's rotation direction is then also the opposite of the intended direction. To prevent this from happening, it is important that the power of the frequency regulator matches the electrical motor and that the settings are correct.

The Dutch Safety Board's partial conclusions on the possibility of the frequency regulator and the trolley motor having failed:

- The trolley motor's power was lessened by the incorrect parameter settings in the frequency regulator;
- Because the power was too low, the trolley motor was unable to turn, or else turned in the wrong direction; and
- The power of the combination of the trolley winch motor and the frequency regulator was not enough to hold the trolley in place, let alone move it up against the slope of the jib calculated in the model, resulting from the flexibility and bend of the crane's mast and jib.

4.4.5 Failure of the trolley cable

The trolley motor pulls the trolley cable back and forth. It pulls on the trolley unit to move the trolley or hold it in place. If the motor is not being operated, the locking brake is activated and the drum around which the trolley cable runs should not be able to move. If the trolley cable breaks, all control of the trolley is lost.

An inspection of the trolley winch from the tower crane in Rotterdam showed that it was still intact after the fall. A static tensile test was therefore performed. That tensile test to the trolley winch cable drum revealed that a tensile force of 13.7 kN was needed to start the cable moving once the brake has been raised. This means that the cable was pulled through the brake at a tensile force of 13.7 kN. The cable's minimum breaking force was 45 kN. This means that the cable would have been pulled through the brake before the trolley cable broke. If the cable is pulled through the brake, no systems are in place to stop the trolley.

If the trolley cable breaks, the control of the trolley is lost, though a safety feature is in place to prevent a major shift. If the trolley cable breaks, the trolley stop will be triggered. As a rule, the trolley stop is held in downward position by the tension on the trolley cable. If the trolley cable breaks, the trolley stop snaps up and runs against the cross connections between the jib's bars.

During the initial period after a new trolley cable has been put into use, it will stretch. The cable then has to be retensioned. In Rotterdam, because of the space created by the stretch in the trolley cable, the trolley stop snapped up several weeks after the crane had been erected, and caught on the jib while the trolley was moving. This caused the stop to break off (though it was subsequently repaired). The trolley stop may work sufficiently if the trolley cable breaks when the trolley is not moving, but not when it is already in motion. According to the Dutch Safety Board, it is more probable that the cable will break while in motion or when being put into motion.

Partial conclusions on the failure of the trolley cable

Based on these findings, the Dutch Safety Board's partial conclusions on the trolley cable are as follows:

– The locking brake is intended only for holding the trolley in place in a situation in which the forces exercised are minor;
– The construction of the trolley stop does not offer an effective security system for the trolley cable breaking while the trolley is moving in or out;
– If the trolley cable breaks, the trolley cannot be controlled.

4.4.6 Slope of the jib

The Dutch Safety Board has found that the constructional calculations were based on a maximum bend of the jib of one degree below level. The result of the manufacturer's calculations with the trolley at 27 metres is 0.6 degrees below level for the tower crane in the configuration used for the crane in Rotterdam. The measurements that the Dutch Safety Board had taken, using a newer – and more rigid - crane revealed that the jib bent 1.2 degrees with 13 tonnes at a radius of 27 metres. FEMTO's calculations for the crane that collapsed, and that was less rigid, show the bend to be 2.1 degrees below level with 13 tonnes on the hook at a radius of 27 metres, and a 5.2-degree bend at a radius of 50 metres. FEMTO's calculations clearly differ from the constructional calculations. The newly erected and more rigid crane also exceeds the maximum bend of

1.0 degree below level that the manufacturer uses as the safety limit in the design, though it clearly bends less than the crane that collapsed. For the Dutch Safety Board, the fact that the manufacturer was not aware of these angles of bend exceeding the bend permitted by the design criteria means that the type of crane had not been tested sufficiently (in all its configurations) before production commenced and that the cranes produced were also not tested sufficiently.

The high angle of bend had a significant effect on the trolley motor's functionality. According to the calculations of the supplier of the frequency regulator, the trolley motor needed 31.6 Nm to hold the trolley in place if the jib sloped 1.0 degrees. With a 2-degree slope, the supplier calculates that 48.5 Nm was needed. The maximum torque that the trolley motor could supply was 49 Nm. In the Dutch Safety Board's view, these calculations show that the trolley winch unit and cable were not up to the task posed by the slope of the jib on the crane in Rotterdam. Without safety measures, or if only one of those measures were to fail, the trolley could move out of its own accord beyond the maximum load moment. This means that the system is not *fail safe*: if a safety measure fails the crane will not automatically revert to a safe position. Only a single safety measure needed to fail to put the crane in a situation in which an overload was inevitable.

Partial conclusions on the slope of the jib

- In this model of tower crane, the jib's slope below level is much greater than permitted in the design, particularly in the configurations of the mast of the crane at Prinsenlaan in Rotterdam;
- The angle of the jib's slope contributes to the other failure scenarios. The barriers that are intended to prevent those scenarios are tested by that slope.
- At the angles of the jib's slope measured and shown in the models, failure of the PLC, the frequency regulator and the trolley motor or the trolley cable will too easily result in the trolley moving out. With a heavy load, this will incontrovertibly cause the crane to collapse.

4.4.7 Beginning of the accident scenario

At the beginning of each scenario an event occurs (often referred to as the initial event) that triggers the scenario. Based on the failure mechanisms, the Dutch Safety Board has established the following probable initial events, given the fact that the tower crane bends further than 1 degree below level:

- EMC malfunctions caused by unprotected cable bus connections;
- The drop in the motor's power caused by incorrect parameter settings in the frequency regulator (particularly when starting a command);
- Insufficient power in the frequency regulator and the trolley motor to pull a heavy load up against the slope of the jib;
- The release of the locking brake before sufficient motor power is generated.

Each of these events separately, or a combination of these events, could have triggered the accident scenario.

4.4.8 Continuation of the accident scenario: trolley moving out beyond the load moment

Once the trolley is moving out of control along the slope of the jib, it is impossible to stop, meaning that the trolley will reach the end of the jib. With a heavy load on the hook, this is far beyond the maximum load moment and beyond the load moment for which the crane was designed. The crane is designed to handle 150% of the maximum load. With 13 tonnes on the hook, the radius for the maximum load moment by design according to the load chart is 40 metres. This means that if the crane collapses with a radius in excess of 40 metres, that does not contradict the crane's design. Essentially, the design is aimed at preventing the maximum load moment shown in the load chart from being exceeded.

In FEMTO's simulation, the crane does not collapse with the 13-tonne load at a radius of 50 metres, based on the calculation of static forces. The simulations with those calculations are sufficient for determining what the collapse mode was and how far the crane's jib had bent. As such, the crane's collapse was caused by the addition of dynamic forces. Examples of dynamic forces include acceleration and deceleration in movements. These may have been caused if, for example, the trolley did not roll out in one smooth motion, but intermittently. Besides acceleration and deceleration, other dynamic forces exist that are caused by vibrations. Those vibrations occur if, for example, the motors' vibrations are transmitted through the steel construction. The pressure on the mast legs increases as a result, and the load that the tower can handle is less. The inevitable dynamic forces were a contributing factor in the collapse of the tower crane's mast.

Partial conclusion on the continuation of the accident scenario

The outward movement of the trolley with its heavy load beyond the maximum load moment as shown in the load chart was what started the accident scenario. The conclusion of the Dutch Safety Board regarding the continuation is as follows:

- Dynamic forces that occurred when the trolley moved beyond the maximum load moment subjected the tower to forces that it could not handle and caused the mast to collapse.

4.4.9 Conclusions on the accident scenario

The Dutch Safety Board concludes as follows in connection with the accident scenario:

- The angle of the jib's slope was too great and put strain the other components.
- A lack of sufficient motor power (possibly combined with a raised brake) in the trolley motor and the bend of the jib at too great an angle meant that the trolley with its heavy load was impossible to control.
- As a result of the forces in play, the load itself moved out beyond the maximum load moment.
- Dynamic forces ultimately caused the crane to collapse, even before the trolley had reached the end of the jib.

4.5 FAILURE MECHANISMS IN THE DESIGN

4.5.1 Control circuits and risk analysis

A control circuit is organised feedback about a product's lifecycle. Various phases can be identified in a product's lifecycle, such as design, production, commissioning, operation and decommissioning. Before the next phase commences, a risk analysis can be carried out to identify and analyse risks. That risk analysis can be used as the basis for conceiving measures aimed at minimising deviations from the envisioned process. The experiences gained in one phase provide input for the next phase and its risk analysis. Effectively organising those analyses in control circuits forms a learning organisation and allows the manufacturer to take responsibility for its own product. This way of working, which may be given shape in many ways, is an important part of the Dutch Safety Board's assessment framework.

The Dutch Safety Board sees no organised development of these analyses in connection with the tower crane in Rotterdam. No risk analyses were documented in connection with the crane's construction, erection or performance. For example, the risks of the jib bending or the possibilities of the LMS failing had not been mapped out. Similar, no tests were performed to determine whether, after production, the design in fact matched the applicable criteria by measuring for the bend of a crane in its standard configuration. Questioning revealed that no specific documented elements for the tower crane in Rotterdam and its design were found during the investigation that match the principle of standard safety management that the Board uses in its assessment framework.

Pursuant to the European Product Directives, a product that falls within the scope of a Directive, i.e. the tower crane in this case, must meet the essential requirements laid down in that Directive. One of those requirements is that a risk assessment of the product be performed. The manufacturer is required to record the design and manufacturing features in the Technical Construction File (TCF). No TCF was available for the crane in Rotterdam. As such, the Dutch Safety Board was unable to determine in what way the manufacturer believes that it complied with the EC Product Directives. For other parties such as buyers, rental customers, users or supervisory authorities that information is then also not readily available. However, the manufacturer's EC declaration of conformity states that the crane meets the essential requirements from the European Machinery Directive, the European Low Voltage Directive and the European EMC Directives and explains what standards were used during construction and manufacturing.

The manufacturer performed some of the technical upkeep and the repairs to the cranes that it sold in the Netherlands. In that work, when malfunctions were resolved the owner or user was not always told what the manufacturer had done to solve a problem, such as installing new software. As a consequence, it is difficult to trace the repair history of a tower crane from the Netherlands.

This means that it is hard to determine whether a clear-cut policy was adopted in connection with control circuits. The modifications made to the first crane in the Netherlands whose trolley had come loose, early in 2008, were not made to other cranes. Nor were they made after the same event happened to a second crane. After the first report of a trolley that ‘shot loose’ during an erection inspection, the manufacturer should have taken responsibility in correctly applying control circuits, for example by reviewing the risk analysis and wondering whether the design contained faults or weaknesses that were the cause of the incident. Modifications were made to that first crane, which initially served to resolve the malfunction. However, the possible design fault had not been remedied. Transparency was also missing in the dealings with the tower crane's owner, caused by lack of proper communication about the way in which malfunctions were resolved and about what measures the manufacturer had taken.

Immediately after the accident in Rotterdam the manufacturer, based on a suspicion about the cause of the accident, took three measures with cranes of the same brand and type in the Netherlands. He fitted those cranes with a reader for determining the rotation direction of the axle of the trolley winch drum. The frequency regulator uses the reader to ‘check’ whether the motor is turning in the right direction. Most of the cranes were equipped with stronger trolley winch motors. The jibs of new cranes yet to be delivered were peaked up by shortening the pulling axle between the topmost tower bar and the masthead by 40 mm. This is a modification to the design. Before these measures can be judged to be sufficient, an investigation must be performed to determine in what scenarios the measures will have sufficient effect, and in what scenarios they will not have any effect, or insufficient effect. For example, it should be determined whether electromagnetic interference may as yet cancel out the measures. Having investigated the measures taken by the manufacturer, the de Dutch Safety Board finds that they help eliminate the underlying causes, but have not been studied to determine whether they are sufficient. That will require the modifications and other failure mechanisms being included in a risk analysis and the effect of the control measures being tested. An example of such a test is to measure the slope of the jib caused by the bend in the crane in the standard configurations for jib length and mast composition as described in the manual.

Partial conclusion on the control circuits

- The manufacturer did not make use of risk analyses, or not sufficient use;
- The manufacturer did not utilise the possibilities of feedback from actual events (such as malfunction reports), or did not utilise those possibilities sufficiently;
- The manufacturer did not sufficiently test the control measures that it implemented in the design requirements in response to certain ‘known’ risks.

4.5.2 Application of harmonised standards

Under the harmonised standards, the manufacturer may legitimately assume, based on the European Product Directives, that it meets the essential requirements laid down in the Product Directive and that as such it is compliant with the state of the art. This means that the results of an investigation into the application of the standards will say nothing about the quality of the product's creation.

Harmonised standards have been issued as a follow-up to the Machinery Directive. Though some of those standards have little concrete meaning for a specific product, several standards apply specifically to tower cranes. At the minimum, application of those standards means that compliance with the state of the art is that much closer.

The tower crane's manufacturer specifies what standards it used in two places. The first of those places is the EC declaration of conformity, while the second is the crane's manual. The EC declaration of conformity for the tower crane is remarkable for the inaccuracies in the document, which comprises a single page.

The first inaccuracy is that it specifies a wrong model for the crane. The manufacturer then states that the product is compliant with the European Product Directives. The references use the numbers of the old, lapsed Directives. The manufacturer also refers to a number of standards. One of those standards refers to the basic principles for steel load-bearing constructions. That standard is not applicable to tower cranes. The reference to another standard, about stability, is to a standard from 1987 rather than to the current version from 1998. Moreover, it is not a harmonised standard. The same is true of two German standards specified in the declaration. For using those standards, the manufacturer must demonstrate that their application results in a level of safety that is comparable to that resulting from the harmonised standards.

The references to the standard for electrical equipment in machinery and the EMC standards are also to standards that were replaced in 2006 and 2001, respectively. The manufacturer then refers to a series of German requirements that are intended for the operational phase, and as such have less bearing on design and production.

By listing standards that have been replaced or are irrelevant, the manufacturer demonstrates a lack of care or of awareness with regard to the current standards. As such, the Dutch Safety Board questions the application of the state of the art. Since no Technical Construction File could be presented, it is impossible to verify whether that conclusion is correct. Further to the shortcomings in the area of risk analysis, the Dutch Safety Board finds that the manufacturer fails to demonstrate that it meets the requirements of the Machinery Directive. As such, the Dutch Safety Board is of the opinion that the manufacturer wrongly issued the declaration of conformity. Based on the documents that the manufacturer provides with the crane, it is impossible to determine whether the crane is compliant with the European Product Directives.

Partial conclusion on the application of the harmonised standards

The Dutch Safety Board has determined the following in connection with the application of the harmonised standards:

- The manufacturer was careless with or insufficiently aware of the current standards;
- The absence of a Technical Construction File makes it impossible for the Dutch Safety Board, as well as, generally, for customers and users of the manufacturer's cranes, to verify whether the crane is nevertheless compliant with the latest state of the art;
- In the opinion of the Dutch Safety Board, the declaration of conformity should not have been issued for this type of crane.

4.6 VALUE OF THE CE MARK

A CE mark means nothing more and nothing less than that the manufacturer of a product believes that that product meets the requirements of the applicable European Product Directives. Exceptions to this rule are the products for which an officially appointed inspection agency (*Notified Body*) must test the design; however, that is not the case with tower cranes. The Dutch Safety Board finds that determining what Product Directives apply and what standards can be used is a complicated issue. It is difficult for manufacturers to determine what Directives and accompanying standards to use. Even if the Directives and standards are specified in the EC declaration of conformity, it is difficult to establish whether the standards applied were the correct ones and whether the manufacturer applied all applicable standards. In the absence of a risk analysis and a Technical Construction File, it is impossible for third parties to determine whether a particular manufacturer actually knows its business and whether it assigned the CE mark correctly. The Dutch Safety Board also finds that, without a list of risks, users may only perceive malfunctions to be troublesome rather than dangerous as well.

The Dutch Safety Board identifies three problem areas in the current system of CE marks for tower cranes. The first problem area identified by the Dutch Safety Board is the application of the CE mark. That process takes place from the moment that that particular type of tower crane goes into production. Once the EC declaration of conformity has been signed, the product may be traded freely and is subjected to little supervision. For tower cranes, the only supervision then consists of the erection inspections and the annual functional inspections. In short, those inspections mostly test the way in which the crane has been erected and the load moment security at the moment of the inspection. If the manufacturer has made any mistakes in the design because of inaccuracy, ignorance or a lack of professional expertise on the use of new technology, no safeguard exists, and the product will not only be sold but will also pass inspection.

The second problem area is the lack of clarity for the product's buyers. To safely use the product, they must observe the requirements set out in the handbook or instruction manual supplied with the product, yet in most cases those documents do not provide a list of the risks taken into account. As such, the risks identified are not explained to the crane's buyer or user. If the buyer is not a specialist, all he can do is trust the manufacturer, without being able to determine or having any indication whether or not that trust is justified.

A third problem area is the lack of feedback and information exchange. Because the tower crane manufacturer only inspects its own product, it does not see what issues other manufacturers of tower cranes have encountered. No platform exists for providing feedback about risks and failure mechanisms.

Partial conclusion on the value of the CE mark

The conclusions of the Dutch Safety Board on CE marks for tower cranes are as follows:
- A CE mark means that the manufacturer believes that it is compliant with European Product Directives, but provides no information about the manufacturer’s knowledge and expertise or about the quality of the product;
- No safeguard exists to remedy errors or incorrect estimates on the part of the manufacturer;
- The European Product Directives do not require that the risk analysis or a list of the risks identified be specified in the product manual, or be communicated to buyers in another manner;
- No European or Dutch forum exists where manufactures and users of tower cranes can share their knowledge about developments or risks in their professions.

4.7 USE OF THE PRODUCT

4.7.1 Trust in the safety and quality of the tower crane

The tower crane that collapsed was first put to use at the construction site in Rotterdam. The crane had been placed on the mounted tower in August 2007, coming directly from the factory. As required by the Working Conditions Act and the Commodities Act, the crane had a CE mark, an EC declaration of conformity and instruction manuals in Dutch and in German (the manufacturer's source language). The tower's configuration fell within the standard configurations presented in the manual. As such, based on the Working Conditions and Commodities Acts the owner had no reason to doubt the quality or the safety of that tower crane.

Before the crane was put into use, it was inspected as required by law, using the certification schedule of the Foundation for the Supervision of the Certification of Vertical Transport. That inspection was carried out by a designated and accredited inspection agency, at the instructions of the new Dutch owner. The crane passed the inspection without any comments. Based on the applicable laws and regulations, the firm renting the crane had no reason to doubt the quality or the safety of the crane that had been erected. That inspection examined the reliability of the crane's construction, the certificates for the cables used and the performance of the LMS, based on a test. In that test, the maximum load is hoisted just off the ground and moved out, to see whether the LMS intervenes in time.

In June 2008, construction work had progressed far enough to require that the crane be raised. The configuration used was not one of the standard configurations in the manual supplied with the crane. However, the manufacturer's design engineer had performed calculations for the configuration, and the manufacturer advised that the crane be erected in accordance with those calculations. As such, the tower crane complied with the regulations for issuing CE marks, and from that perspective the owner and the contractor had no reason to doubt the crane's quality or safety. At the owner's instructions, the crane was inspected by the same inspection agency, which issued the certificate with one reservation. Since no test for hoisting with the maximum load could be conducted with the correct hoist cable, the owner would have to perform that test later. The owner signed off on that test in the crane log some days later, and passed that information on to the inspection agency. As such, based on the certification schedule everyone could legitimately assume that the crane was up to standard.

The Dutch Safety Board finds that the certainty about the proper functioning of the crane relies on trust in various issues. The users, the contractor hiring the crane and the operator working it, trust the manufacturer and the owner of the crane. They receive confirmation that the crane is up to standard from the crane log and the instruction manual. They cannot see the CE mark automatically, since it is placed in the top of the crane. The crane log shows that the inspection agency approved the crane and that according to the manufacturer the crane is compliant with the Product Directives that apply to tower cranes. This is also the basis of the owner's trust. Based on those documents, the parties do not automatically obtain information about the risk considerations involved in the crane's design and construction. For that information and for an indication of the care observed during the work, users of tower cranes must take the initiative to request additional information from the owner/rental firm of the manufacturer.

The Dutch Safety Board finds that an inspection according to the certification schedule is typical for when cranes are *erected*. The inspection focuses primarily on the construction and the care observed during the erection. Less attention is given to the crane's *performance* under normal or non-standard operating conditions. The result is tested exclusively by hoisting the maximum load and by verifying whether the load moment security intervenes at the right moment.

Considering the technical expertise on the subject that is necessary to understand how the crane as a whole functions, the manufacturer and the owner, but the user (the contractor) as well, have to rely on specialists. For the owner of a crane, this means that it is important to gain a better understanding in order to become less dependent on the manufacturer. Many users do not possess that expertise and remain dependent on the owner and the manufacturer. However, this does not alter the fact that the user may take the initiative to ask the owner or the manufacturer for information about parts of the Technical Construction File, such as the risk analysis, or to explain the work that was performed during maintenance or to remedy a malfunction. For example, larger firms hiring tower cranes commission agencies with sufficient technical understanding of the subject to perform a type inspection whenever they are considering hiring a new model of crane.

Partial conclusion on the trust in the safety and quality of the tower crane

Users who do not possess sufficient expertise and skill of their own to judge the safety and quality of a tower crane depend on the expertise and skills of others. The Dutch Safety Board concludes the following with regard to trust in the safety and quality of the tower crane:

- Based on the applicable regulations, none of the parties involved had any reason to doubt the safety and quality of the tower crane;
- The owner and the user lacked information about the specific risks attached to the tower crane in question and the ways to control those risks;
- Their lack of the necessary technical expertise meant that the owner and the user were very much dependent on the manufacturer;
- Neither the owner nor the user saw any reason to ask for additional information about the risks and the accompanying control measures.

4.7.2 Comparison with earlier incidents with tower cranes

When considering an incident, the Dutch Safety Board addresses the question of whether the incident is unique or whether it is the consequence of a structural problem. The Dutch Safety Board also tries to consider the gravity of the problem. The frequency of similar incidents and their consequences are important factors in that consideration.

Problems when considering incidents with tower cranes are that few records are kept of accidents and that that information is not readily available. Incidents with tower cranes or other types of cranes are not registered at the industry level. The Labour Inspectorate records accidents that are reported to that agency. Accidents involving fatalities or personal injuries are required to be reported. Other incidents are sometimes also reported. It is not always possible to infer from the Labour Inspectorate's collected data what type of crane was involved in a particular incident and what the cause was. As such, no reliable numerical pronouncements can be made about the frequency of incidents with tower cranes caused by technical factors.

Two of the four cranes discussed in section 2.4 collapsed while they were being erected. One of those cranes fell over because insufficient ballast had been used, as a result of administrative mistakes and a careless attitude towards the manufacturer's instructions. No similarities can be found with the incident at Prinsenlaan in Rotterdam.

The other three incidents display a degree of similarity with the incident in Rotterdam. In hindsight, each of those cases involved an incomplete or imprecise identification and analysis of the risks. In Cuijk, the problem lay in the assumptions surrounding the crane's foundation. In the court's opinion, the correct assumptions could have been made if a standard for the technical principles for building constructions had been applied. It is apparent, however, that the feeling in the industry is that too little information is available about how to accurately calculate the foundation of a crane in relation to the ground below. The incident at Brielselaan in Rotterdam revolved around the way in which the foundation was fastened. The risk that the bolts in the connection work loose while the crane is being used had not been identified. It subsequently became apparent that this was not the only case in which those bolts had developed some play over time. In the incident in Utrecht, it was assumed that the tower crane would move into weathervane position if it was in weathervane mode in strong wind, which ultimately proved not to be the case. The assumptions concerning the crane's behaviour in strong wind were therefore incorrect. This unusual behaviour of the crane in weathervane mode had already been noted by a crane operator.

In all these incidents, it would have been beneficial if the knowledge of the incident had been shared, because the same situation may also occur with other cranes. Each crane must be placed on a foundation that suits the ground under it. Various types of cranes develop play in the bolt connections. Any crane standing near high buildings may have to deal with swirling winds. And each type of crane has to deal with rapid electrotechnical developments. This information is not shared with the rest of the industry.

In two cases the tower crane fell on a building, causing considerable damage such as knocking down walls and roofs. In both incidents, people in those buildings were the victim of the incidents, and were injured or even killed. At Prinsenlaan in Rotterdam, too, the falling crane caused a great deal of damage where it hit the building. As a result of the falling walls and roofs, it may even be more dangerous in a building than in the open air if a tower crane collapses.

Partial conclusion on the comparison with earlier incidents with tower cranes

The Dutch Safety Board did not study the four earlier incidents with tower cranes in the Netherlands itself, but based its examination on documentation supplied by the Labour Inspectorate and other parties. In the Board's opinion, the incident with the crane at Prinsenlaan in Rotterdam involved a lack of proper identification of risks and testing of assumptions on the part of the manufacturer. In that connection, the Board's conclusions, comparing this incident with earlier incidents, are as follows:

- In each incident, insufficient account was taken of the risks of the construction or configuration of the crane or of working with tower cranes;
- The assumptions relating to risk analysis or user limits were not tested sufficiently;
- In each of the incidents, either the accident scenario was known before the incident (relationship between the foundation and the ground, lack of sufficient ballast), or observations had been made of non-standard behaviour with which a scenario could have been posited (bolt connections, non-standard behaviour in weathervane mode);

4.8 SHORTCOMINGS

The Dutch Safety Board has revealed four failure mechanisms in the design of the tower crane at Prinsenlaan in Rotterdam that led to the trolley's unintended outward movement. This phenomenon forms a serious hazard for the crane balance and stability. The slope of the jib at an angle below level and the added force that gravity then exercises on the trolley moving toward the point of the jib seriously exacerbates the other failure mechanisms. The more rigid configuration of the new tower crane that was erected displays a smaller angle, yet one which still exceeds the maximum angle on which the calculations in the design were based. The Dutch Safety Board regards those failure mechanisms as serious structural shortcomings in the tower crane's design. To prevent similar incidents in the future, the possibility of unintended outward movement of the trolley must be eliminated and the bend of the jib must be made to match the design criteria.

The unintended outward movement of the trolley occurred on several occasions before the incident in Rotterdam, with different models of that brand of tower crane. The Dutch Safety Board concludes from this that this structural shortcoming applies not only to this one model, but also to other models of the same brand. After each report of a trolley moving out, the manufacturer took measures for an individual crane, without applying them to the whole product series. Based on this finding, it is the conclusion of the Dutch Safety Board that the manufacturer did not recognise the shortcomings as structural shortcomings in the design and working methods (insufficient risk assessment).

Because the manufacturer did not perform any risk analyses for the correlation between the separate parts, the shortcomings were not identified. Such risk analyses are especially important because, besides constructive modifications, the electronic components in particular are becoming increasingly complicated and as a result it is more and more difficult to maintain a proper understanding of those systems. That is why, in accordance with the principles of safety management used by the Dutch Safety Board, designs must be subjected to extensive risk analyses based on all failure scenarios imaginable. The designs and the safety measures must then be tested again before a new crane is put into production. The bend of the crane's jib in situations with different mast configurations is an example.

Next to the design, the use of control circuits, as required by the principles of safety management, is also vital for ensuring that products and systems remain operationally functioning and safe. This is true both for the manufacturers and for the owners and users of the cranes. The conclusion of the Dutch Safety Board is that the parties involved did not make sufficient use of the experiences gained to understand and learn from the earlier incidents. In short, insufficient guarantees were in place to ensure that these cranes could be worked with safely.

If the manufacturer had observed greater care in applying the prescribed and available standards, some of the problem areas identified could have been remedied. The availability of a Technical Construction File with the risk analyses prepared increases the possibilities for learning from incidents. Transparency in dealings with owners and users is an important factor in this regard. They can put forward problem areas encountered in operation, which the manufacturer can then turn into modified user instructions or design modifications.

The Dutch Safety Board believes that a structural safety shortcoming lies in the absence of a safeguard. Besides the manufacturer, no one monitors shortcomings in the design or production. Owners, and particularly users, of tower cranes generally lack sufficient knowledge and information to judge whether or not the cranes are operating safely. Carelessness and lack of knowledge on the part of a manufacturer are not filtered out on the market until serious incidents occur so frequently that the market develops an aversion to certain products. Considering the potentially serious consequences of tower cranes collapsing in places where building cranes are situated close to large concentrations of people, this is an undesirable situation.

Two developments might serve to create a safeguard. The first is to amend the European Machinery Directive. If tower cranes were to be included in Annex IV of the Directive, they would become hazardous machinery that must be inspected by Notified Bodies. A second possibility is to change the requirements for use, specifically the inspection requirements, defined in the certification schedule of TCVT. At present, the inspection requirements in the Netherlands are one-sided and oriented toward the *structural* features of tower cranes and a single test of the load moment security. That schedule could be expanded to include the assessment and testing of various of the crane's parts and functions and ensuring that parts of the Technical Construction File are available.

Conclusions

Based on the investigations and analyses performed and as described in the previous chapters, the Dutch Safety Board's partial conclusions are as follows:

Partial conclusions on the causes underlying the collapse of the tower crane at Prinsenlaan in Rotterdam:

1. The combination of the heavy load at too great a radius with the excessive bend of the jib severely limited the trolley's functioning - within the operational limits - and as such formed the basis for the collapse of the tower crane.

2. Before introducing the crane to the market, the manufacturer did not investigate and test the tower crane's design for specific risks. Those risks concern the combination and effect of the complex of components.

3. The failure to properly identify and analyse risks is not restricted to this model of crane, but may also apply to all models of this brand of tower crane. Other incidents with tower cranes of other brands also reveal a lack of sufficient risk identification and analysis. This is also true of the feedback of information from incidents in practice.

Partial conclusions on the shortcomings (failing barriers) in the design of the tower crane:

4. The logic rules in the *Programmable Logic Controller* are not sufficiently geared towards the possible events, meaning that error messages do not always lead to an appropriate action. The module for the PLC's load moment security offers insufficient certainty as a barrier against the load moment being exceeded.

5. Incorrect parameter settings in the frequency regulator and the limited power of the trolley motor meant that there was insufficient certainty that the trolley could be moved in the intended direction or be held in place. This meant that an important barrier against the unintended outward movement of the trolley failed.

6. The crane's design does not take the possibility of the trolley cable failing sufficiently into account. If the trolley cable is not on the brake or if it breaks, an outward movement, once started, cannot be stopped and the unintended outward movement of the trolley cannot be prevented.

7. In this model of tower crane, the bend of the jib below level is much greater than the design criteria permit. This is a major contributing factor in the failure scenarios of PLC, frequency regulator and trolley motor and trolley cable. This constitutes a serious threat to the stability of this tower crane.

Partial conclusions on the frame of reference

8. The inspection requirements as laid down by the Foundation for the Supervision of the Certification of Vertical Transport TCVT are one-sided and focused on construction after the crane is erected and on testing the maximum load limiter, and do not focus sufficiently on checking the performance of the control and security systems.

9. The transparency of risks, risk analyses and safety measures in tower cranes is poorly visible and not sufficiently open to the estimates of the users of tower cranes.

Partial conclusions on a safeguard to reveal and help prevent accidents resulting from shortcomings in design or production if, contrary to what the manufacturer believes, a tower crane is not compliant with the European Product Directives:

10. A manufacturer that makes mistakes in a design and the assessment thereof, that is less precise or lacks sufficient knowledge of certain subjects, may state that it believes that the product meets the requirements of the European Product Directives without that actually being the case.

11. Tower cranes are not included in Annex IV of the Machinery Directive, based on which machinery is considered 'hazardous'. Those types of machines are subject to a regime involving inspections by a Notified Body before the product may be introduced to the market.

The final conclusions of the Dutch Safety Board based on the investigation into this incident are as follows:

- The crane collapsed because in practice it did not match the manufacturer's design criteria;

- The manufacturer's production process does not include guarantees to prevent deviations from the design criteria, which is not in accordance with the principles of safety management[1].

- Preventing failure in the chain of design, production and use of tower cranes is an issue that is addressed and guaranteed in neither the European Product Directives nor the national laws and regulations.

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[1] Principles of safety management: To understand risks, to adopt a demonstrable and realistic safety plan, to implement and enforce that safety plan, to improve on the safety plan and to show the involvement of management through control and communication (see section 3.5).

5 RECOMMENDATIONS

In light of the findings and conclusions emerging from the investigation, the Dutch Safety Board argues that current European regulations offer insufficient means to control the existing risks, and the Board wishes to put forward the following recommendations:

Recommendations to the Minister of Social Affairs and Employment:

1. Arrange the creation of a registration centre for accidents and near-accidents involving cranes, including tower cranes. One of the purposes of that registration centre should be to warn all parties involved of any dangerous situations. The registration centre should be supported by a platform consisting of representatives from the industry: crane manufacturers and owners, users and principals.

2. At the European level, advocate the inclusion of tower cranes in the list of hazardous machinery in Annex IV of the Machinery Directive.

Recommendations for the Foundation for the Supervision of the Certification of Vertical Transport:

3. Expand the certification schedule for tower cranes by adding functional test criteria. Those criteria should encompass not only the subjects that address mechanical failure but also those that address failures in electronics and the controls of the tower crane.

The administrative bodies to which a recommendation is addressed must notify the relevant minister of their position on how to follow up on that recommendation within six months after this report is published. Non-administrative bodies or persons to whom a recommendation is addressed must notify the relevant minister of their position on how to follow up on that recommendation within one year. Copies of that response must be sent to the Chair of the Dutch Safety Board and to the Minister of Foreign Affairs and Kingdom Relations at the same time.

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