Master Thesis

Introducing a BIM-based Spatial-Temporal Collision Detection Model to Avoid Work Zone Traffic Accidents in Municipal Construction Projects

Author: Gerco Mussche

Date: 22 May 2024

This page is intentionally left blank.

Introducing a BIM-based Spatial-Temporal Collision Detection Model to Avoid Work Zone Traffic Accidents in Municipal Construction Projects

A thesis submitted in partial fulfilment of the requirements for the degree of
Master of Science in Construction Management & Engineering

COLOPHON

Author
G. Mussche (Gerco)
s2093723
g.mussche@student.utwente.nl

Version
Final

Front Page Image
Veenenbos en Bosch landschapsarchitecten

Colloquium Date
22 May 2024

Education
Faculty of Engineering Technology
Master’s in Construction Management and Engineering
Profile: Digital Technologies in Construction

Educational Institution
University of Twente
Drienerlolaan 5
7522 NB Enschede
(053) 489 9111

Commissioning Organisation
Roelofs Groep B.V.
Kroezenhoek 8
7683 PM Den Ham
(0546) 67 88 88

Graduation Committee

dr. S.R. Miller (Seirgei)	*Chair of the committee*
dr. ir. F. Vahdatikhaki (Farid)	*Supervisor University of Twente*
ing. J.H. Withaar (André)	*Supervisor Roelofs Groep B.V.*

PREFACE

Dear reader,

In front of you lies the master thesis titled “Introducing a BIM-based Spatial-Temporal Collision Detection Model to Avoid Work Zone Traffic Accidents in Municipal Construction Projects”. This study has been performed at Roelofs Groep B.V. as a final assignment for my master Construction Management & Engineering, and it shows the need and also presents means to improve the safety in the construction industry by reducing struck-by danger. This thesis concludes my academic career at the University of Twente, where I started with the Bachelor Industrial Engineering and Management in 2018 and leave 5½ years later to start my professional career as a civil engineer, which I am very much looking forward to.

This achievement would not have been possible without the contribution of several people. First of all, I am profoundly grateful to André Withaar, my supervisor at Roelofs, who has been very cooperative and helpful to me and was always available for my questions. Moreover, I would like to thank all the employees from Roelofs that I interviewed for this research, who contributed a lot to this research with their practical knowledge.

Furthermore, I would like to express my gratitude to Farid Vahdatikhaki for his supervision on behalf of the University of Twente, whose constructive criticism steered me in the right direction at the beginning of this research and kept me motivated in the latter stage. A special thanks goes to Seirgei Miller for his willingness to be the chair of the graduation committee.

Enjoy reading!

Gerco Mussche

Enschede, April 2024

EXECUTIVE SUMMARY

The construction industry is a dangerous sector, and struck-by accidents are the second largest cause of accidents in the sector. These accidents can be classified into accidents that are caused by equipment in the work zone itself, and those that are caused by road traffic adjacent to the work zone. The focal point of this research is placed on struck-by road traffic accidents, because Roelofs can exercise a certain degree of control over equipment in the work zone, but they have limited control over external factors such as the behaviour of road users, road conditions, and traffic flow. To protect their construction workers from traffic hazards, a good construction site layout is essential which is why Roelofs should take the adjacent traffic already into account in the design phase, but current design practices are not sufficient to understand adequately what the dangerous areas of a construction site are. According to the literature, this could be done by analysing workspace conflicts. Using BIM to analyse workspace conflicts has been done by several authors for the building industry, but it has not been applied to the road construction industry while it could potentially be applied for the planning of temporary roads and stacking locations in municipal road construction projects. Therefore, the research objective of this study is as follows:

“To develop a BIM-based method based on an analysis of the root causes of work zone related traffic accidents in municipal road construction projects, that assesses this risk in order to make designers aware of how their design choices impact struck-by hazards caused by road users.”

The first step in achieving this objective is to explore which sections of work zones or specific construction activities in municipal road construction projects lead to potential collision danger between project resources and road users. To do so, five recent projects of Roelofs are examined by conducting semi-structured interviews with project leaders or superintendents to gather insights. The interviews focus on identifying construction activities contributing to accidents and the general experiences of participants regarding struck-by danger. As a solution to the identified hazards, almost all interviewees stated that a work zone should be completely demarcated from all road users. Although it might be difficult to convince clients to entirely close essential roads, one of the interview participants expects that this can be done by means of a spatial planning that indicates the lack of space for road users to pass the work zone. For such a planning, the following key learning points from the interviews serve as the input:

1. Since access intrusion was mentioned by every interviewee, the to-be-developed tool should contain an option to predict the behaviour of road users, i.e. road users should have the option in the simulation to leave the predefined path and intrude the work zone in an attempt to find a shorter route.
2. Attention should be paid to the hazard spaces of construction activities because these spaces are often neglected due to a lack of space, which is why the spatial-temporal analysis should easily indicate if these guidelines are maintained.
3. Next to static workspaces, the collision detection tool should contain the option to model dynamic workspaces, because such moving workspaces are also a major risk based on the interviews (e.g. caused by construction vehicles that enter or leave the work zone).

The proposed methodology consists of four sequential steps: building model preparation, traffic simulation, workspace generation and allocation, and site safety assessment. In the first step, the current infrastructure is added to the 3D model and the project planning is added to create a 4D model. In the second step, the temporary routes are added to the model and the traffic is simulated, the workspaces are added in the third step, and in the fourth step is the algorithm implemented that detects conflicts between workspaces and traffic spaces. After executing this methodology for an existing project, the

following struck-by hazards were detected: access intrusion, buffer intrusion, and working outside the designated work zone. To mitigate these risks, two countermeasures were evaluated for the case project:

1. During certain activities, cyclists should walk next to their bicycles on the promenade to prevent that the excavator and the cyclists use the same road.
2. During certain activities, traffic lights should regulate the cars to prevent that the roadway next to the work zone is used in two directions.

These measures prevented almost all struck-by risks in the case project, hence the case study shows that the developed methodology can be used for the planning of temporary roads through layout planning and collision experiments, although it first needs to be developed further. Some suggestions for the next development steps are: modelling other construction activities and associated workspace types that are relevant based on the semi-structured interviews but not incorporated in this research, and increasing the usability of the tool by building an interactive user interface.

MANAGEMENTSAMENVATTING

Dit onderzoek is uitgevoerd voor een Nederlands bedrijf, en om het onderzoek toegankelijk te maken voor alle medewerkers bevat dit verslag naast een Engelse managementsamenvatting ook de Nederlandse versie hiervan.

De bouw is een gevaarlijke sector en aanrijdgevaar is de de op één na grootste oorzaak van ongevallen in de sector. Deze ongevallen kunnen worden ingedeeld in ongevallen die worden veroorzaakt door machines in het werkvak zelf en ongevallen die worden veroorzaakt door wegverkeer naast het werkvak. De focus van dit onderzoek ligt op aanrijdgevaar door weggebruikers, omdat Roelofs een bepaalde mate van controle kan uitoefenen over machines in het werkvak, maar slechts beperkte controle heeft over externe factoren zoals het gedrag van weggebruikers, de toestand van de weg en de verkeersstroom. Om hun medewerkers te beschermen tegen aanrijdgevaar is een goede inrichting van de bouwplaats essentieel en daarom moet Roelofs al in de ontwerpfase rekening houden met het aangrenzende verkeer, maar de huidige ontwerppraktijken zijn niet toereikend om goed te begrijpen wat de gevaarlijke gebieden van een bouwplaats zijn. Volgens de literatuur kan dit worden gedaan door conflicten tussen werkruimtes te analyseren. Verschillende auteurs hebben dit door middel van BIM gedaan voor de bouwsector, maar het is nog niet toegepast op de wegenbouwsector, terwijl het mogelijk zou kunnen worden toegepast voor de planning van tijdelijke wegen en opslaglocaties in binnenstedelijke wegenbouwprojecten. Daarom luidt de onderzoeksdoelstelling van dit onderzoek als volgt:

"*Het ontwikkelen van een BIM-gebaseerde methode op basis van een analyse van de hoofdoorzaken van aanrijdgevaar door weggebruikers in binnenstedelijke wegenbouwprojecten, die dit gevaar beoordeelt om ontwerpers bewust te maken van hoe hun ontwerpkeuzes van invloed zijn op aanrijdgevaar door weggebruikers*."

De eerste stap om dit doel te bereiken is te onderzoeken welke delen van een werkvak of specifieke werkzaamheden in binnenstedelijke wegenbouwprojecten leiden tot potentieel aanrijdgevaar tussen door weggebruikers. Daarvoor werden in dit onderzoek vijf recente projecten van Roelofs onderzocht door middel van semi-gestructureerde interviews met projectleiders of uitvoerders. Bijna alle geïnterviewden verklaarden dat een werkvak volledig moet worden afgebakend van alle weggebruikers. Hoewel het misschien moeilijk is om opdrachtgevers te overtuigen om essentiële wegen volledig af te sluiten, verwacht een van de deelnemers aan het interview dat dit kan worden gedaan door middel van een ruimtelijke planning die aangeeft dat er geen ruimte is voor weggebruikers om de werkzone te passeren. Voor een dergelijke planning dienen de volgende belangrijke leerpunten uit de interviews als input:

1. Aangezien toegangsindringing door elke geïnterviewde werd genoemd, moet de te ontwikkelen tool een optie bevatten om het gedrag van weggebruikers te voorspellen, dus weggebruikers moeten in de simulatie de optie hebben om de vaste route te verlaten en het werkvak binnen te dringen in een poging om een kortere route te vinden.
2. Er moet aandacht worden besteed aan de gevarenruimtes van werkzaamheden omdat deze ruimtes vaak worden verwaarloosd. Daarom moet de ruimtelijk analyse aangeven of deze richtlijnen worden gehandhaafd.
3. Naast statische werkruimtes moet de tool ook de optie bevatten om dynamische werkruimtes te modelleren, omdat dergelijke bewegende werkruimtes ook een groot risico vormen op basis van de interviews (bv. veroorzaakt door bouwverkeer dat het werkvak binnenkomt of verlaat).

De ontwikkelde methode bestaat uit vier opeenvolgende stappen: voorbereiding van het digitale ontwerp, simuleren van het verkeer, genereren van werkruimtes, en de beoordeling van de veiligheid op de bouwplaats. In de eerste stap wordt eerst de bestaande situatie toegevoegd aan het 3D-model en dan de projectplanning toegevoegd om een 4D-model te creëren. In de tweede stap worden de (tijdelijke) verkeersroutes aan het model toegevoegd en wordt het verkeer gesimuleerd, in de derde stap worden de werkruimtes toegevoegd, en in de vierde stap wordt het algoritme geïmplementeerd dat conflicten tussen werkruimtes en verkeersruimtes detecteert. Na het uitvoeren van deze methode voor een bestaand project werden de volgende gevallen van aanrijdgevaar gedetecteerd: toegangsindringing, bufferindringing en werken buiten het werkvak. Om deze risico's te beperken, werden twee maatregelen getest voor het case project:

1. Tijdens sommige werkzaamheden moeten fietsers naast hun fiets op de promenade lopen om te voorkomen dat de graafmachine en de fietsers dezelfde weg gebruiken.
2. Tijdens sommige werkzaamheden moeten verkeerslichten de doorstroming van auto's regelen om te voorkomen dat de rijbaan naast de werkzone in twee richtingen wordt gebruikt.

Deze maatregelen hebben bijna alle gevallen van aanrijdgevaar in het case project voorkomen. Dit onderzoek laat dus zien dat de ontwikkelde methode kan worden gebruikt om tijdelijke wegen en werkruimtes te plannen, alhoewel de ontwikkelde tool wel eerst verder ontwikkeld moet worden voordat deze in de praktijk gebruikt kan worden. Enkele suggesties voor de volgende ontwikkelingsstappen zijn: het modelleren van andere werkzaamheden en bijbehorende werkruimtes die relevant zijn op basis van de semigestructureerde interviews maar die niet in dit onderzoek zijn opgenomen, en het vergroten van de bruikbaarheid van de tool door het bouwen van een gebruikersinterface.

TABLE OF CONTENTS

TABLE OF TABLES

TABLE OF FIGURES

GLOSSARY OF TERMS

Term:	**Meaning:**	**Page:**
AABB	Axis-Aligned Bounding Box	18, 42
BIM	Building Information Modelling	6-7, 9-13, 29, 33
BGT	Basisregistratie Grootschalige Topografie	34, 37
CROW	Centrum voor Regelgeving en Onderzoek in de Grond-, Water- en Wegenbouw en de Verkeerstechniek	15, 22, 24-25, 27, 34, 39, 41, 44, 51, 53
IFC	Industry Foundation Class	9, 13
LOD	Level of Development	10-12
NLA	Netherlands Labour Authority	1, 5
MVD	Model View Definition	13, 37
OBB	Oriented Bounding Box	18
OSHA	Occupational Safety and Health Administration	1
SAT	Separating Axis Theorem	18-19, 31, 43
SI	Severity Index	17, 31, 43
SSI	Site Safety Index	17, 31-32, 43-44, 46

1

INTRODUCTION

1.1 COMPANY INFORMATION

This research is carried out at Roelofs Groep B.V., referred to as Roelofs in the rest of this report. Roelofs is an engineering firm and contractor in the infrastructure sector. Their expertise includes among other things rural development, mobility, water, sewerage, and raw materials. They are involved in all phases of a project: from advice and design to realisation, management, and maintenance. Moreover, Roelofs is always looking for innovative solutions, such as innovative asphalt mixtures, innovative contract forms, and data-driven road management (Roelofsgroep, n.d.-a). With regard to safety, Roelofs recently reached step 3 of the Safety Culture Ladder (Roelofsgroep, 2022). As Figure 1 shows, this third step is called "Calculating" and means that "*the company has determined which safety rules are important, adopts a vulnerable approach and assumes responsibility, but is often driven by self-interest. Involvement in safety and compliance with rules and laws is mainly the task of (senior) management. Attention is given to health and safety, which is valued*" (Safety Culture Ladder, n.d.). This shows that safety is really important within Roelofs, and the research that is described in this thesis is a next step in their never-ending journey to improve the safety of their employees.

Figure 1: The Safety Culture Ladder steps

1.2 RESEARCH CONTEXT

The construction industry is a dangerous sector. According to the Netherlands Labour Authority (NLA), 110 accidents per 100.000 employees occurred in 2021 in the Dutch construction industry, which made it the sector with the second most accidents (NLA, 2022). Rubio et al. (2005) mentioned several characteristics of the construction industry that cause this high accident rate: the construction site is often unknown beforehand, all projects are unique and have mostly a short duration, many subcontractors are hired, workforce training is scarce, and workers are often exposed to bad weather conditions. The Occupational Safety and Health Administration (OSHA) uses five basic categories to classify construction accidents: falls (from elevation), shocks (electrical), caught in/between, struck-by, and other. According to several studies, such as the ones by Gürcanli & Müngen (2013) and Hinze et al. (1998), the largest causes for construction accidents are falling from heights and struck-by accidents. However, it is not clear what is actually understood by the term struck-by accidents. For some people, struck-by accidents relate to equipment, while others relate it to materials handling (Hinze et al., 2005). The OSHA distinguishes between four categories of struck-by accidents: struck-by a flying object, struck-by a falling object, struck-by a swinging object, and struck-by a rolling object (OSHA, 2011). In the road construction industry, struck-by a rolling object accidents are the most common of these four. These accidents are defined by the OSHA as "*instances in which the worker is struck or run over by a moving vehicle* *without being caught under it or instances in which the worker is struck-by a sliding object or equipment on the same level*" (OSHA, 2011, p. 10). Struck-by a rolling object accidents can be further classified into accidents that are caused by equipment in the work zone itself, and those that are caused by road traffic adjacent to the work zone (NLA, n.d.). Next to that, it is important to note that there is a difference between struck-by and struck-against accidents: a struck-by accident occurs when an object strikes the worker and the force of contact is provided by the object, while in a struck-against accident the worker strikes the object. The majority of struck injuries are caused by struck-by incidents (Brown et al., 2021). The focal point of this research is therefore placed on struck-by road traffic accidents, so accidents where the force of contact is provided by the traffic. Here, road traffic refers to all road users: cars, cyclists, pedestrians, etc., because they can all be involved in collision accidents. These road users can collide with construction workers or with construction objects such as materials and equipment, and these collisions can be dangerous for both the construction worker and the road user. This focal point is chosen because Roelofs can exercise a certain degree of control over equipment in the work zone, but they have limited control over external factors such as the behaviour of road users, road conditions, and traffic flow. Therefore, this research aims to decrease the danger of adjacent traffic in their construction projects, and Section 1.3 further explains what this danger entails.

1.3 DANGERS OF ROAD TRAFFIC

Construction workers are often exposed to the dangers of working close to road traffic if the road is kept accessible for its users during maintenance or construction (Nnaji et al., 2018). However, closing public roads completely during construction projects is impossible since the transportation function of most roads often cannot be missed, construction vehicles should be able to enter and leave the work zone safely, and emergency services should not be hindered from passing the work zone. This means that safety and accessibility sometimes conflict with each other. The danger of collisions between construction workers and road traffic is illustrated by a news article in The Washington Post which reported that six road construction workers died after a car crashed into them (The Washington Post, 2023), or by an accident in the Netherlands where a construction worker died after a truck driver ignored the signals and barriers that indicated the construction work and entered the work zone, where the fatality happened (Algemeen Dagblad, 2014). Luckily, these are exceptional cases, but every construction worker experiences quite often near misses, where accidents are narrowly avoided. According to multiple studies, one in ten road workers experiences a near miss every year (Venema et al., 2008; VVN, 2023).

According to Venema et al. (2008), there are two causes of potential struck-by road traffic accidents: the road worker enters the traffic zone, or the road user enters the work zone. The first category is illustrated by Bryden et al. (1998), who mention the danger of construction vehicles that are entering, exiting, or crossing open travel lanes, (i.e. these vehicles are entering or exiting the defined work zone), and by Bryden & Andrew (1999) who pay attention to the danger of construction workers who cross travel lanes or work in another way outside the defined work zone. With regard to the second category, a distinction can be made between five sources of accidents resulting from road users entering the work zone (Bryden et al., 2000):

- Full intrusion: a vehicle enters a fixed work zone or buffer space that is defined by channelising devices (such as traffic cones, barricades, or barriers).
- Buffer intrusion: vehicles do not enter the work zone, but accidents occur within the lateral buffer space (see Figure 2). Generally, these accidents involve sideswipe accidents, contact with the mirror of a passing vehicle, or contact with overhanging objects on a passing vehicle.
- Moving work zone intrusion: this type of intrusion involves cars that enter a work zone that is not defined by channelising devices, but instead by work vehicles, flaggers, or similar means.
- Access intrusion: accidents that occur when a vehicle deliberately intrudes a work zone in an attempt to move through the work zone and gain access to a driveway. This type of intrusion often occurs among cyclists and pedestrians: if the additional distance of the temporary route is

too large, they tend to find their own alternative routes by crossing the work zone (CROW, 2011).
- Debris intrusion: debris is thrown into the work zone by a passing vehicle and it hits a construction worker or a piece of equipment.

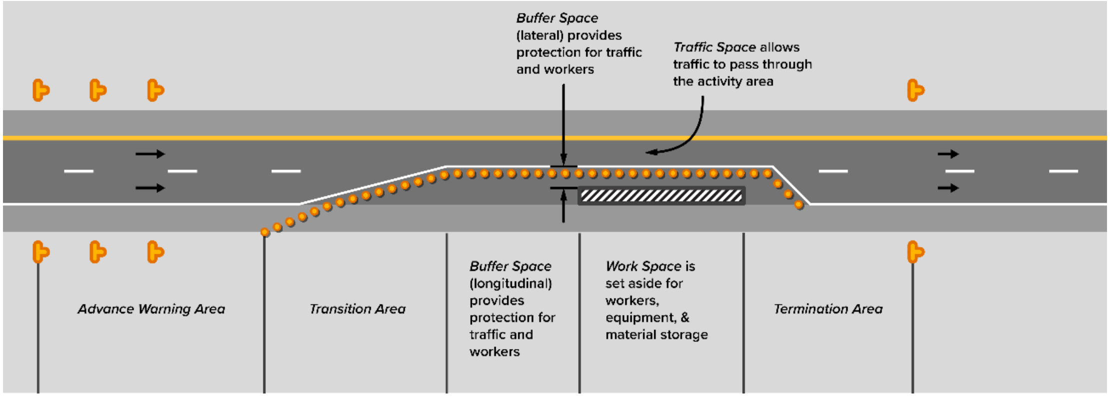


Figure 2: Work zone layout (Nevada LTAP, n.d.)

These causes for struck-by accidents are shown in Figure 3. Bryden et al. (2000) discovered that excessive speed, driver incapacity (caused by e.g. alcohol, sleep, or medical conditions), and driver inattention are the greatest contributing factors for dangers with road traffic, and most measures to prevent intrusion accidents are therefore focused on alerting drivers (Sakhakarmi & Park, 2022). However, a later study by Ullman et al. (2011) concluded that a significant portion of intrusion accidents can be accounted to deliberate driver decisions to enter the work zone. Some reasons for these deliberate decisions are wanting to reach a desired exit or intersection, simply following a construction vehicle into the work zone, or ignoring the instructions of flaggers. These findings indicate that it is insufficient to solely alert drivers, and that is equally important to protect construction workers from potential intrusions (Sakhakarmi & Park, 2022).

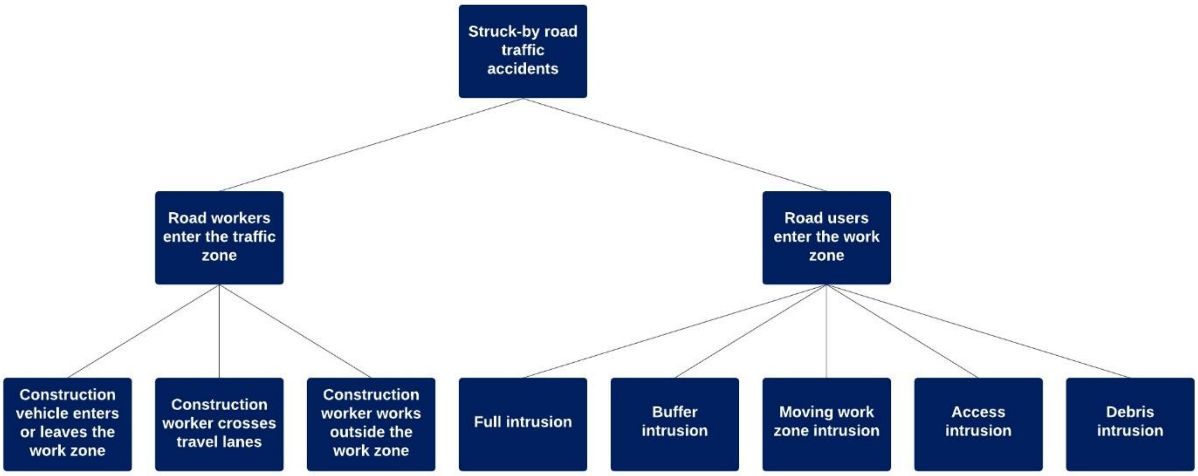


Figure 3: Causal relationships for struck-by road traffic accidents

Shehab & Phu (2015) analysed 204 traffic accidents in road construction zones that occurred between 1999 and 2009 in the city of Buena Park (California, US). They described the following characteristics of these accidents: the time, day, month, and year of occurrence, the lightning condition, type of collision (e.g. head-on or rear end), the primary collision factor (e.g. unsafe speed or unsafe lane change), objects involved with collision (e.g. pedestrians or other motor vehicles), severity, weather condition, roadway surface condition, and the presence of traffic control devices. Some of their findings are that 98% of road work zone accidents result in property damage and injuries, and 0.5% of these accidents result in fatalities. Next to that, they discovered that rear-end collisions occur the most often (34%), followed by right-angle accidents (27%) and sideswipes (20%). They also concluded that 98% of accidents could be attributed to human errors such as speeding and driving on the wrong side of the road. Similar data was collected by the Minnesota Department of Transportation (2015), which also investigated work zone safety from a traffic crash perspective based on 5,569 accidents between 2012 and 2014. According to Wong et al. (2011), 68% of all accidents with road traffic happen on the highway while only 4% of these accidents occur on a city street. Based on this statistic, it appears that highway construction projects are more dangerous, but it is also likely that accidents in urban road construction projects are often not reported.

The abovementioned research has two major limitations. First of all, a limitation of analysing accidents is that the danger on a construction site is not fully captured by solely describing accidents, but near misses also play a huge role in construction site safety. Two definitions of near misses are "*incidents in which no injury actually occurred but the potential for an injury existed*" (Hinze & Godfrey, 2003, p. 7), and "*incidents where no property damage and no personal injury was sustained, but where, given a slight shift in time or position, damage and injury easily could have occurred*" (Shen & Marks, 2016, pp. 2–3). A common problem in the construction industry is that these incidents are often not reported, due to a missing infrastructure for reporting these accidents and a lack of motivation at organisations to share feedback with the worker who reported the incident (Teizer & Cheng, 2015). Hall & Lorenz (1989) confirm that the frequency of accidents in road construction work zones is substantially greater than accident records indicate. One of the few studies that interview road workers about their experience with near misses is the one by Venema et al. (2008), who found that work zone related traffic accident causes to which road workers are most often exposed are speeding, noise, insufficient demarcation of the work zone, and a lack of space in the work zone. However, one of the things that this study does not make clear is in which concrete situations a lack of space in the work zone could lead to collisions by road traffic. Investigating this is in line with a suggestion for further research from Shehab & Phu (2015), who said that work zone related traffic accidents could be explored from the perspective of a contractor, for example by investigating the sections of work zones or the specific construction activities where accidents occurred.

The second limitation is that the presented studies, as well as others that are not mentioned yet (e.g. Arditi et al. (2007); Kim et al. (2013); Li & Bai (2008)), focus on highway construction projects while accidents with road traffic on municipal streets have received little attention in the literature. However, these streets are an interesting research topic because Liu et al. (2019) describe municipal road construction as complex since it is carried out in areas with a large urban traffic flow where traffic diversion is often difficult. Next to that, there is a large number of construction equipment, materials, and personnel on municipal road construction sites, but the construction site is often narrow and surrounded by many buildings and a large flow of people and traffic. As a result, it is difficult to store construction materials, and the temporary storage of equipment and materials can cause traffic congestions which leads to safety hazards (Gan & Ge, 2023). Therefore, this research will shift its focus to road construction projects that do not involve highways. With road construction projects, we understand a wide range of infrastructure operations, including but not limited to (re)constructing asphalt and brick roads and subsurface renovations (see Kuiper et al. (2007, pp. 58–60) for an extensive list of possible infrastructure operations). Since most studies focus on highway projects, other road users than cars (such as cyclists and pedestrians) are often not taken into account in these studies, but they play a huge role in this research since they are present near municipal road construction projects. We assume that the abovementioned dangers (Figure 3) also apply to municipal road construction projects and other road users than cars, but additional research is needed to investigate the root causes of these dangers in municipal road construction projects. In the literature, it is found that many authors point to design choices as the underlying cause for struck-by danger. This concept is referred to as "Safety by Design" and is explained further in Section 1.4.

1.4 SAFETY BY DESIGN

Nowadays, contractors experience an increasing competition in the construction industry, which means that they have to utilise their equipment and workers optimally and execute as many construction activities simultaneously as possible. This parallelisation of construction activities and high employment of resources often leads to spatial conflicts since the working space is limited on a construction site (Marx & Köning, 2013). Some examples of spatial conflicts between construction activities and road usage that are experienced by Roelofs are if a trench is dug for subsurface renovations near a busy road and designers have not taken into account a storage space for the soil that is retrieved from the trench, or bricklaying or asphalt paving operations nearby a busy road which result in unsafe situations. These unsafe situations can be explained by the limited site space as one of the characteristics of a road construction project (Choi et al., 2014). Each activity on a construction site requires a certain occupational volume during its execution, and if this space is simultaneously occupied by multiple activities, a spatial conflict occurs which leads to safety hazards (Messi et al., 2022a). A study by Venema et al. (2008) among 534 road workers confirms that the main cause of work zone related traffic accidents is insufficient working space. Therefore, workspaces are one of the most important constraints to manage at a construction site (Elsheikh, 2022), and the resource site space is as important as money, time, material, labour, and equipment (Hegazy & Elbeltagi, 1999).

The NLA points out that the adjacent traffic and the movement of equipment within the work zone should already be taken into account in the design phase (NLA, n.d.). So, a good site layout is essential for providing a safe construction site environment, but the safety assessment of a construction site layout has been neglected in the literature (Ning et al., 2018). This is in line with the experience of Roelofs: their designers do not take into account if the road traffic is a hindrance for certain construction operations or vice versa, and if these operations can be executed safely. However, many studies have already stressed that the potential for accidents is drastically reduced when safety is planned from the beginning of a project (Szymberski, 1997). This author introduced the time/safety influence curve (Figure 4), which shows that the ability to influence safety decreases rapidly after the pre-construction stages and that the ability to influence safety is low at the start of the actual construction (Lingard et al., 2014).

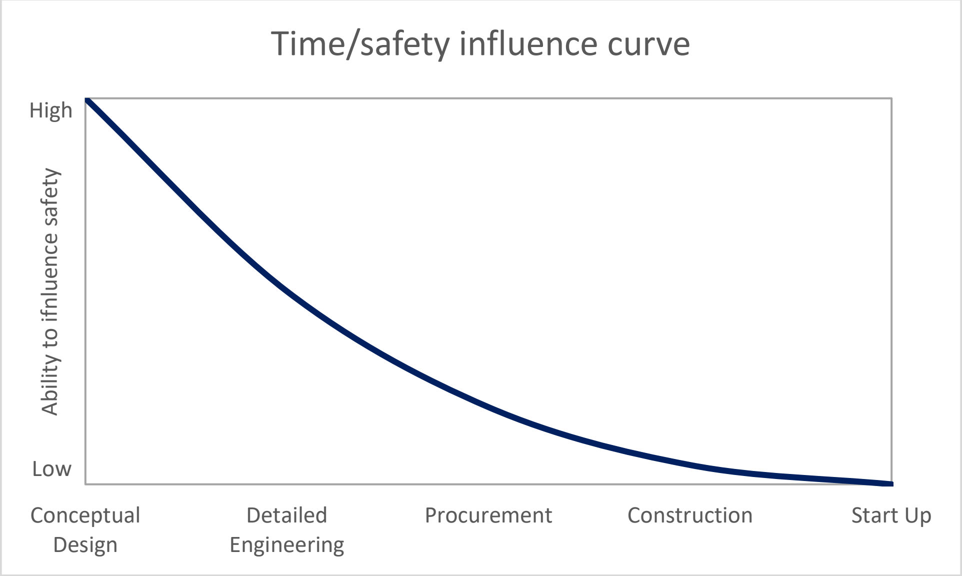


Figure 4: The time/safety influence curve

The validity of Syzmberski's time/safety influence curve was confirmed by Lingard et al. (2014) and Karakhan et al. (2018) who used empirical data and statistical evidence to prove that the ability to influence safety drastically decreases as a project progresses through the different stages, by Behm (2005) who reviewed 224 cases of construction accidents and concluded that 42% of the incidents could have been prevented with design changes, and by Malekitabar et al. (2016) who revealed that 46.8% of construction accidents are related to design choices and that certain risks can be avoided by changing the design. This implies that designers should be aware of how their design choices impact on-site safety, but current safety plans often consist of 2D paper-based information (Shafiq & Afzal, 2021) which makes it difficult to detect potential spatial collisions because humans have limited skills to mentally simulate future conditions (Guo et al., 2017; Zhang, Sulankivi, et al., 2015). As a result, Larsen & Whyte (2013) raised questions about the knowledge and capabilities of designers to understand safety and stressed the importance of visualising safety in design practices. Thus, this section showed that it is important to consider collision danger in the design phase of construction projects and that current design practices are not sufficient to understand adequately what the dangerous areas of a construction site are. Therefore, Section 1.5 describes how the incorporation of safety in the design phase can be improved by using BIM.

1.5 BUILDING INFORMATION MODELLING

As a means for improving safety in the construction industry, Building Information Modelling (BIM) has already been used for over a decade. For example, Johansen et al. (2022) state that automated prevention through design can be done by defining a link between construction regulation and the BIM model and then defining the logic that checks whether the regulation is violated in a BIM model. This corresponds with the structure that Eastman et al. (2009) developed to implement a functionally complete rule-checking and reporting process. This structure is implemented by among others Zhang et al. (2013), which resulted in a method for detecting and preventing fall-related hazards. With regard to struck-by accidents, most authors agree that workspace conflicts are the main cause of these accidents. For example, Hammad et al. (2012) proposed a method for collision prevention that automatically generates Dynamic Virtual Fences based on the workspaces of construction equipment, Vahdatikhaki & Hammad (2015) presented a method for generating dynamic equipment workspaces based on the pose, state, geometry, and speed characteristics of the equipment, Shang & Shen (2016) introduced a BIM-based framework to evaluate on-site collisions, and Heidary et al. (2021) presented a semi-automatic method based on 4D BIM to identify hazardous attributes that can cause struck-by accidents. There are even more studies that analyse workspace conflicts as a solution for struck-by accidents, such as Akinci et al. (2000), Elsheikh (2022), Dawood & Mallasi (2006), Mirzaei et al. (2018), and Zhang et al. (2015). What all these studies have in common, is that they focus on the building industry instead of road construction. This implies that BIM is less developed for horizontal construction than it is for vertical construction, which is confirmed in the literature. Costin et al. (2018) and Liu et al. (2019) say that although BIM has been widely adopted in the building industry, the road construction industry has been slow in its adoption and application. Gan & Ge (2023) mention that BIM can be applied in the construction of municipal roads for the planning of temporary roads and stacking locations through layout planning and collision experiments by simulating the construction plan, identifying the existing problems in the construction planning, and combining the construction progress and road characteristics to effectively plan the temporary roads. This has to the best of the authors' knowledge not been done so far, which means that using workspace conflict analyses in BIM to analyse struck-by danger caused by road traffic is still a literature gap.

1.6 RESEARCH DESIGN

1.6.1 Research Objective

Firstly, this section provides the problem statement that summarises the sections above and points out the identified literature gaps. The problem statement is twofold and contains the following key points:

1. In many municipal infrastructure projects, adjacent public roadways that are used by cars, cyclists and pedestrians cannot be closed which increases the danger of collisions between road users and project resources (e.g. workers, equipment, and materials). Studies investigating such struck-

by accidents often focus on highway construction projects, but municipal road construction projects have received little attention in the literature. Moreover, near misses also play a huge role in construction site safety but it has not been investigated how they are caused. Therefore, work zone related traffic accidents and near misses in municipal infrastructure projects should be explored from the perspective of a contractor by investigating the sections of work zones or the specific construction activities where accidents and near misses often occur.

2. Congested construction sites and conflicting workspaces are widely regarded as the main cause of struck-by accidents, and therefore it is important to consider collision danger in the design phase of construction projects in order to design a safe construction site. However, current design practices are not sufficient to understand adequately what the dangerous areas of a construction site are, and visualisations of spatial conflicts by using BIM could contribute to that understanding. Using BIM to analyse workspace conflicts has been done by several authors for the building industry, but it has not been applied to the road construction industry.

These key points in the problem statement are interrelated because the answer to the first problem serves as the input for solving the second problem. This results in the following research objective:

"To develop a BIM-based method based on an analysis of the root causes of work zone related traffic accidents in municipal road construction projects, that assesses this risk in order to make designers aware of how their design choices impact struck-by hazards caused by road users."

The intended outcome of this research is a BIM-based tool that assesses and visualises spatial-temporal conflicts between construction activities and road users in road construction projects and quantifies the associated risk. The purpose of this tool is to raise awareness among designers on how their design affects road users, and this tool contributes to their understanding of how to reduce the risk of work-zone-related and struck-by incidents on a construction site. A possible intervention resulting from this tool can be that contractors can ascertain that certain projects are unsafe if the traffic keeps using its normal routes and that roads should be closed completely and other temporary routes should be found.

1.6.2 Research Questions

Now that the research objectives are clear, the next step is to define the research questions that can help to achieve the objectives. These questions are as follows:

1. What are the main causes of struck-by accidents and near misses with road users in road construction projects?
2. Which specific sections of work zones or construction activities and their associated workspaces have an increased risk of struck-by accidents?
3. How can designers be made aware of these potentially hazardous situations?
    a. What information should be added to a BIM model?
    b. How can struck-by danger be detected and quantified in a BIM-based tool?
    c. Are the results from this BIM-based tool valid?
    d. What are the requirements of this BIM-based tool for its use in practice?

1.6.3 Research Methodology

This research starts by creating a solid foundation for the to-be-developed tool. This is firstly done by conducting a literature review in Chapter 2 where several topics that form the basis of the tool are investigated further (such as BIM, multiple classifications of spatial-temporal conflicts, and serious game engines), and secondly by conducting a multiple-case study in Chapter 3 where five projects of Roelofs are examined. In each case study, semi-structured interviews with practitioners are used to explore the perceptions of workers regarding work zone hazards. The interviews aim to answer research questions 1 & 2, because this combination gives more insight into the dangerous construction activities and their associated workspaces, but also identifies the root causes of struck-by accidents which familiarises the researcher with the broader perspective of the subject instead of focusing solely on the available spaces.

The novel methodology that integrates the BIM model of a construction project, its work schedule, and the (temporary) traffic routes during the project with a spatial conflict simulator is presented in Chapter 4. The proposed methodology consists of four sequential steps: building model preparation, traffic simulation, workspace generation and allocation, and site safety assessment. After a tool is developed based on this methodology, these steps are implemented in a case study in Chapter 5. At the end of Chapter 5, the developed tool is evaluated by using a statistical analysis for verification, and the feedback of experts from Roelofs is the input for the validation of the tool.

Research questions 2a and 2b are both answered in three distinct phases of the research: in the literature review to explore the foundations of these questions, in designing the methodology for the spatial-temporal analysis in order to tailor the foundations of the literature to the specific purpose of this research, and in a case study where the methodology is executed. Under research question 2c, the verification and validation of the case study results is executed, and research question 2d is answered in the discussion (Chapter 6) and conclusion (Chapter 7), where the developed tool is evaluated, its use for practice is discussed and some additional research suggestions are given that can develop the tool further.

2

LITERATURE REVIEW

This literature review first aims to review the concept of BIM, since the collision detection method that is presented later in this thesis is entirely based on it. After providing an extensive definition of BIM and its dimensions (Section 2.1.1), this section describes the main characteristics of BIM models, including the Level of Detail and Level of Development (Section 2.1.2), the application of BIM in infrastructure design (Section 2.1.3), and an introduction to the interoperability problem (Section 2.1.4). Next, the literature on spatial-temporal conflicts is investigated, by exploring the different kinds of workspaces (Section 2.2.1), the existing methods to find the dimensions and location of workspaces (Section 2.2.2), the possible results of workspace conflicts (Section 2.2.3), and how these conflicts can be detected and quantified (Section 2.2.4). This literature review finishes by reflecting on serious game engines as a suitable tool for executing a spatial-temporal analysis in Section 2.3.1.

2.1 BUILDING INFORMATION MODELLING

2.1.1 BIM maturity levels and dimensions

There is no common, widely accepted definition for BIM (Doan et al., 2019; Migilinskas et al., 2013). The World Economic Forum defines BIM as "*a collaborative process in which all parties involved in a project use three-dimensional design applications, which can include additional information about assets' scheduling, cost, sustainability, operations and maintenance to ensure information is shared accurately and consistently throughout total assets' lifecycles*" (World Economic Forum, 2018). BIM is sometimes misunderstood as solely a 3D model, but it is mainly about the lifecycle information management and the 3D model is just one way of representing this information (Costin et al., 2018). BIM consists of multiple maturity levels (Flores et al., 2018), and Figure 5 shows that four maturity levels exist from 0 to 3. Level 0 represents the traditional design methods such as 2D drawings and manual documentation. Level 1 refers to the stage where 3D models are used for a visual representation of the building data. However, these 3D models are not linked together, and there is only partial collaboration between project teams by using a common data environment such as Microsoft Teams or Google Drive to access all information (Eischet, 2023). Real effective collaboration starts at level 2, where team members use a common file format such as the Industry Foundation Class (IFC) for their 3D models. Level 3 is the top level and means full collaboration and full integration. Every project team uses the same shared model that allows them to modify and improve the model in real-time. As can be seen in Figure 5, each maturity level is associated with several BIM dimensions.

The first dimension is the documentation of all requirements of a construction project, 2D and 3D BIM involve modelling a project in two and three dimensions, and 4D and 5D BIM incorporate respectively the project schedule and project budget into the design (Ershadi et al., 2022). According to several authors (Charef et al., 2018; Ershadi et al., 2022; Wildenauer, 2020), there is no consensus about the dimensions beyond 5D. Sampaio et al. (2022) consider 6D as the energy usage and sustainability studies in the execution and operation stages and 7D as the management and maintenance of the building in the operation stage, while Kamardeen (2010) and Flores et al. (2018) define 6D as facilities management and use 7D for sustainability. Possible interpretations of even higher dimensions are that 8D BIM involves onsite health and safety requirements, 9D integrates lean construction requirements into the design, and 10D aims at full industrialisation of the construction industry (Ershadi et al., 2022).

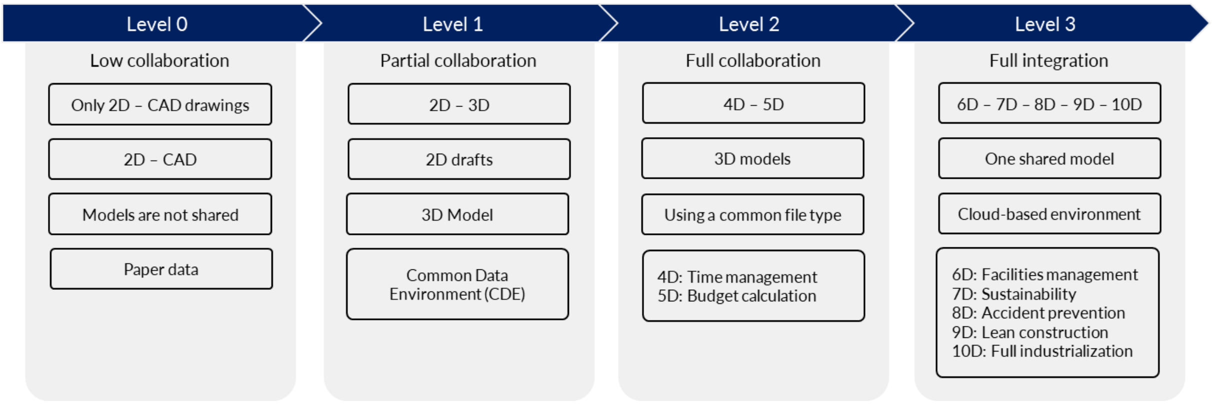


Figure 5: BIM Levels, dimensions and required standards, based on Flores et al. (2018)

However, several authors have questioned the relevance of all these dimensions (Koutamanis, 2020; Wildenauer, 2020). According to Koutamanis (2020), BIM dimensions beyond 3D (nD) often focus on applications and their results but it remains unclear what is added to the 3D model. 4D BIM already contains the data that is used for the calculation of other dimensions. Therefore, the author argues that higher dimensions do not qualify as dimensions in BIM since these dimensions refer to information that is already present in the 3D or 4D model. Therefore, instead of using BIM dimensions beyond 4D, Wildenauer (2020) suggests that clients should clearly state which data and information they need. This also solves possible confusion caused by the lack of consensus on what the higher dimensions are, as described above.

Nevertheless, Shafiq & Afzal (2021) mention several possible applications of 8D BIM, such as a 4D-based safety model according to rule-based checking, visualisation of workspaces, analysis of near miss areas during construction, and BIM and RFID tags to track workers, equipment, and materials. As the five biggest advantages of using 8D BIM, Hire et al. (2021) mention site layout planning, visualisation and simulation of construction hazards and measures, early management of hazardous equipment and materials, rapid and effective decision-making, and on-site safety monitoring and control. Ajibade (2020) adds that BIM allows team members to have visualised safety training before a construction task is carried out. But despite all the benefits of 8D BIM, it also has some limitations that cannot be overlooked. First of all, there is a certain reluctance towards embracing new technologies in the construction industry (Dubois & Gadde, 2002; Gambatese & Hallowell, 2011), the market is not ready yet and there is a lack of competent BIM professionals (Gambatese & Hallowell, 2011). Furthermore, implementing 8D BIM comes at a high cost which makes it challenging for small and some medium-sized contractors to purchase the required software and hire new BIM professionals, and finally some BIM software libraries do not contain safety features and equipment yet (Ajibade, 2020).

2.1.2 Level of Detail and Level of Development

In a BIM model, the Level of Detail refers to the degree of graphical detail or representation of a building element in the model. A high Level of Detail indicates a detailed and accurate model, while a lower Level of Detail represents building elements in a simplified form. It primarily deals with the visual representation of an object or component in the model (Abualdenien & Borrmann, 2022; Trani et al., 2015; Uusitalo et al., 2019). The Level of Development, on the other hand, refers to the degree of completeness and information availability for a 3D BIM model (Figure 6). At a low Level of Development, the information about a building element may be limited to basic parameters such as its name, type, and location, while a higher Level of Development provides data such as dimensions, material specifications, and performance attributes (Abualdenien & Borrmann, 2022; Latiffi et al., 2015; Van Berlo & Bomhof, 2014). So, the amount of project information that is included in a BIM model is continuously growing from the conceptual phase until the construction phase. BIM Onderwijs (n.d.) summarises the difference between the Level of Detail and Level of Development as follows: if a radiator is defined down to product level (i.e. the brand and type of the radiator are known) it is in the last stage of the Level of Development even if the graphical representation is just a bounding box, but if no other information is known besides the fact that the object is a radiator, the design is in one of the first stages of the Level of Development no matter how detailed the graphical representation is.

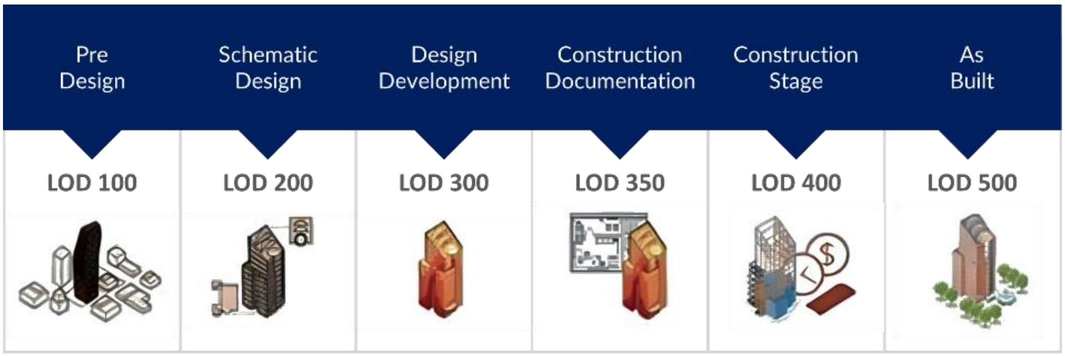


Figure 6: 3D BIM Level of Development (Monarch Innovation, 2023)

With regard to the application of 8D BIM, Collado-Mariscal et al. (2022) state that health and safety are often addressed in an advanced stage of the design phase, where the Level of Development is relatively high. The reason for this is that risks are associated with certain tasks, and these tasks are related to specific BIM objects, and the geometric definition and associated information depend on the Level of Development of the BIM model. Therefore, the risk assessment depends on this Level of Development, but according to Collado-Mariscal et al. (2022), it is also very important to address construction safety at earlier design stages.

4D-LOD:	4D-LOD description:	Units of time:	3D LOD:	Purposes:
A	Demonstrative/ summary	Month to week	100-300	Strategic: Illustration and communication of a summary plan.
B	Major work coordination and feasibility analysis	Week to day	100-400	Strategic/tactical: Choosing the best scenario option for the project.
C	Contractual baseline at the time of bid	Day to hour	200-400	Tactical: Confirmation of the feasibility of a selected scenario.
D	Operational fieldwork	Days to minute	300-500	Operational: Progress and control measurement. Shows facility manager operations and equipment relocation.
E	Detailed equipment movements and workspaces	Hour to minute	300-500	Operational: Avoidance of spatial-temporal conflicts and enabling logistics planning.

Table 1: Comparison of various 4D LODs (Guevremont & Hammad, 2019, 2020)

According to Guevremont & Hammad (2019), integrating a 3D BIM model with the project schedule results in a 4D simulation that has a certain Level of Development as well (4D-LOD). These authors introduce five 4D-LODs, which are based on established 3D-LODs and schedule LODs (Table 1). This 4D-LOD typically increases throughout a project. They say that the 4D-LOD D is adequately detailed for the generic movement of equipment and general workspaces such as prisms, but at the 4D-LOD E, detailed workspaces for crews and equipment can be added to consider the spatial-temporal criticality aspects of the project. Workspaces are detailed and adjusted specifically to follow equipment and resource movements, which enables the user to detect spatial-temporal clashes and to resolve these clashes by modifying the mock-up and/or the schedule.

2.1.3 BIM in infrastructure design

BIM has been widely adopted in the building industry but the road construction industry has been slow in its adoption and application (Chong et al., 2016; Costin et al., 2018; Liu et al., 2019). One of the differences is that infrastructure design is more complex than building design because it comprises often many kilometres and interferences with the environment (Vignali et al., 2021). Therefore, accurate georeferences are of major importance, which can be achieved by aligning Geographical Information Systems (GIS) and BIM. These differences are shown by the development of the BIM dimensions: most applications of BIM to detect and prevent hazards focus on the building industry instead of road construction, and even the use of lower dimensions such as 4D is not common practice in road construction. The research by Zanen et al. (2013) is one of the few studies that focuses on developing 4D models for horizontal construction work to support project planning. They investigated how highway construction work impacts the public, due to hindrance and reduced accessibility of traffic networks, noise, dust, and vibrations for example. An explanation for this lacking BIM development is that fragmentation is a major barrier that prevents successful IT implementation in the road construction industry (Agdas & Ellis, 2010). The constantly changing project partners result in technical issues in creating IT applications and problems with justifying the required investment. Next to that, the adversarial relationships between the project partners focus on improving the profit of the individual parties, instead of improving the overall efficiency of the entire supply chain. Moreover, Siebelink et al. (2021) found that the willingness of people to start using BIM, their competencies in using BIM, and their capacity to make and support the organisational transition to BIM are the main barriers that hinder the adoption of BIM among contracting firms.

Chong et al. (2016) analysed the adoption and use of BIM in major infrastructure projects in Australia and China. Their analysis revealed instances where BIM applications diverged from those commonly seen in the building sector. These applications are more relevant for infrastructure projects than building projects due to their complex project characteristics, and also more feasible due to the large capital investment that is involved with infrastructure projects. The mentioned applications include the following:

- Avoiding traffic congestion caused by construction operations by simulating various transportation alternatives based on the surrounding environment.
- Infrastructure projects affect many stakeholders or residents, and a web-based interface of the BIM model can inform and engage the public about the construction progress.
- The integration of BIM with GIS for site setting-out and surveying, which is beneficial due to the need for accurate georeferences and boundaries for the construction site.
- Monitoring and controlling the construction progress more effectively via capturing data by CCTV and transferring this data back to the BIM model.
- Applying laser scanning to detect deviations in the construction progress.
- The use of 3D printing to check if the structural integrity of the model is sufficient, to simulate certain construction processes and to determine the requirements and availability of workspaces.

2.1.4 Interoperability and Model View Definitions

Section 2.1.3 already mentioned the fragmentation in the construction industry, which means that a construction project involves practitioners from multiple disciplines, and often they all use different BIM software for their own purpose. The problem that then emerges is that information is structured in different formats and cannot easily be exchanged between the different systems, which hinders the creation of one centralised BIM model (Lee et al., 2015; Sampaio et al., 2022). This is often called the interoperability problem, where interoperability can be defined as "*the ability of diverse systems and organisations to work together (interoperate)*" (Venugopal et al., 2012, p. 412). As mentioned in Section 2.1.1, real effective collaboration between project teams starts by using a common file format such as the IFC, which is a specific data format that enables the exchange of BIM models between different systems without losing any data (Sampaio et al., 2022). Since a building model is usually quite huge with many object relations that are not relevant for the majority of applications (Borrmann & Rank, 2009), a Model View Definition (MVD) can be used to specify the information that is required for the application (Zhang et al., 2013). A MVD is a subset of the IFC, and it is often used by specific disciplines to export specific model information instead of the entire model (Krijnen & Van Berlo, 2016; Lee et al., 2015). This allows for a more efficient execution of the application for which the building model is used.

2.2 SPATIAL-TEMPORAL CONFLICTS

2.2.1 Workspace Classification

As shown in Section 1.5, many studies have already investigated the issue of workspace management and most studies use different classifications of workspaces. Choi et al. (2014) classify workspaces by function (direct or indirect use) and by movability (fixed or flexible). Direct workspaces are spaces required for the transformation of inputs into outputs such as object-, working- and storage spaces, which are also referred to as value-adding activities. Indirect workspaces are the required spaces to facilitate transformation activities such as setup-, path- and unavailable spaces (also referred to as non-value-adding activities). Akinci et al. (2002) distinguish between macro-level spaces (storage, staging, layout, unloading, and prefabrication areas), micro-level spaces (crew, equipment, building components, hazard, and protected areas), and paths (spaces for transporting people, material, and debris). Guo (2002) divides workspaces into four categories: labour-, equipment-, material- and temporary spaces, and Mirzaei et al. (2018) use the categories labour crew workspace, equipment space, hazard space, product space, temporary structure space, and material storage space. Chavada et al. (2014) use the categories main workspaces for value-adding tasks, support workspaces for non-value-adding tasks, object workspaces for building materials, and safety workspaces to prevent safety hazards. The most elaborated classification that was found in the literature is the one by Riley & Sanvido (1995), who identified 12 different space usages for construction activities:

1. Layout area: the space that is required for determining the position of materials that are placed by an activity.
2. Unloading area: the space that is occupied by or required for unloading materials on the construction site.
3. Storage area: the space that is required for keeping materials or tools from the time that is delivered to the site until it is used.
4. Work area: the space that is required by labourers to execute certain construction activities;
5. Material path: the space that is required for moving materials from unloading areas to storage- and work areas.
6. Staging area: the space that is required to temporarily arrange materials for short intervals of time.
7. Personnel path: the space that is required for labourers to travel between two points on a construction site.

8. Prefabrication area: the space that is used to prepare, prefabricate, or assemble building components.
9. Tool and equipment area: the space that is occupied by a temporary facility which is used to support other construction activities.
10. Debris path: the space that is needed for the disposal of packaging material and other waste;
11. Hazard area: the space that is unusable due to dangers.
12. Protected area: the space that is used to protect resources.

It is important to note that this classification was made for the construction of multi-story buildings, but we assume that these spaces also exist on a road construction site. The last workspace classification that is discussed is the one proposed by Igwe et al. (2022). This classification (Figure 7) uses two broad categories of workspaces: direct and indirect workspaces. Their definitions are already explained above, and the workspaces in Figure 7 can be further classified as static or dynamic. Static workspaces are spatial-temporal invariant which means that the space is fixed during the execution of the activity, and instances of static workspaces are the motion patterns of equipment (Figure 8), stored materials, and workers who stay at a single location (Shang & Shen, 2016). Dynamic workspaces are spatially variable and are for instance workers who move between different locations and mobile machinery. Dynamic workspaces are a combination of the motion pattern of an activity and its movement path (Mirzaei et al., 2018; Shang & Shen, 2016; Teizer & Cheng, 2015).

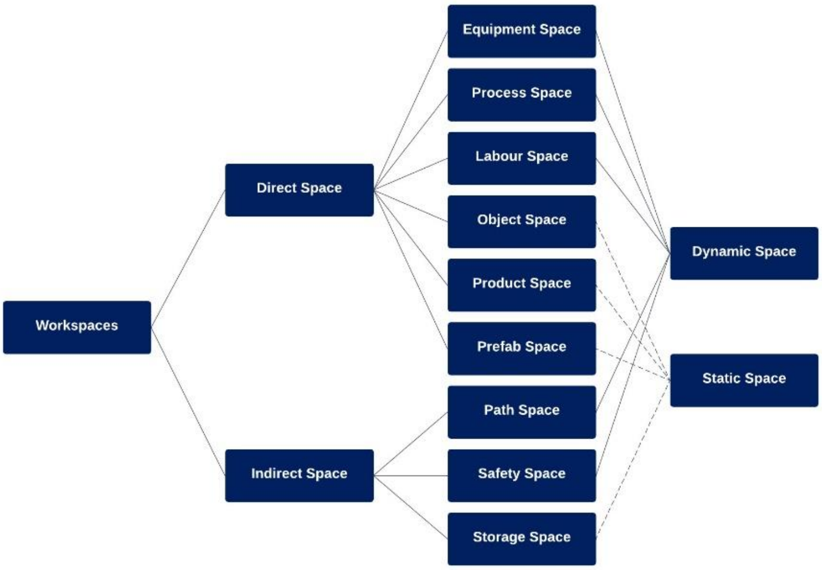


Figure 7: The workspace classification of Igwe et al. (2022)

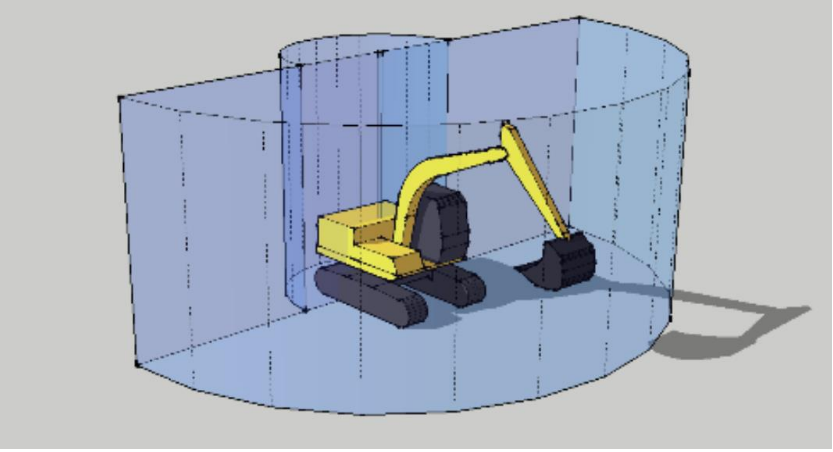


Figure 8: The motion pattern of an excavator (Shang & Shen, 2016)

2.2.2 Workspace Generation and Allocation

Workspace generation is the process where the shape and size of a workspace are determined, while workspace allocation is the process where the location of these workspaces is determined (Elsheikh, 2022). Elsheikh (2022) distinguishes between two methods to generate workspaces and allocate them to tasks: solid geometry-based, and cell-based. In the solid-based method, space usage is represented by geometric elements, and both static and moving objects can be modelled by this method. In the cell-based method, space usage is represented by grids and cells. Intensive calculation is required for this method since a huge amount of cells is being processed. This method is used to analyse the movability of on-site objects and path planning issues (Wang et al., 2019). In this research, we opt for the solid-based method, because we think that using bounding boxes for the static and moving objects to represent space usage is most useful in this research. It has two advantages: these bounding boxes are relatively easy to model, and clashes among solid-based workspaces are easily detectable because the workspaces are geometric elements and clash detection is a common function in most BIM software programs (Igwe et al., 2022; Wang et al., 2019). For the allocation of workspaces, their location or motion path has to be determined depending on whether it is a static or dynamic workspace, respectively. The generation and allocation of the hazard spaces of an activity are based on several handbooks from the Dutch Centre for Regulation and Research in Civil Engineering and Traffic Technology (CROW). These handbooks, which are also online available, contain detailed guidelines for the recommended hazard spaces of roadworks on non-highways (CROW, 2020a, 2020b).

2.2.3 Workspace Conflict Classification

Workspace conflicts have three unique characteristics: their existence is limited to a certain period, they occur in different forms that could change together with the requirements of the task they are allocated to, and they can create different types of problems, such as hazards for construction workers or reduced productivity. Conflicts between workspaces are called spatial-temporal conflicts, and their impact depends on the interfering workspaces (Mirzaei et al., 2018). Akinci et al. (2000) identified five major types of workspace conflicts:

1. Design conflict, which occurs when a building component conflicts with another building component.
2. Safety hazard: when a hazard space conflicts with a work area it creates a dangerous situation for the labourers.
3. Damage conflict: this occurs when the space that is needed for a construction activity overlaps with a protected area, which was required to protect resources during the construction activity.
4. Congestion: this is caused when spaces that are needed by multiple construction activities overlap with each other. If that is the case, the conflicting activities cannot be executed concurrently as planned, which results in productivity losses. The authors distinguish between mild, medium, and severe congestion.
5. No impact: sometimes the spatial overlap between two different spaces does not result in problems on the construction site.

Table 2 shows the taxonomy of spatial-temporal conflicts that was developed by Akinci et al. (2000) through performing case studies at four different construction sites. Further clash types may exist, and an addition to the work of Akinci et al. (2000) is the usage of the clash types work interruption, space obstruction, and access blockage (Dawood & Mallasi, 2006; Mallasi, 2004, 2006). Since this research investigates conflicts between traffic spaces and construction workspaces, the taxonomy of Akinci et al. (2000) has to be expanded with traffic spaces. The literature does not contain a workspace conflict classification that includes traffic spaces, but it is assumed that traffic spaces have the same clash types as equipment spaces, since their behaviour and danger is quite comparable on road construction sites.

	Storage space	Labour space	Equipment space	Hazard space	Protected space	Temporary structures
Storage space	Congestion	Congestion	Congestion	No impact	No impact	Severe congestion
Labour space	Congestion	Congestion	Congestion	Safety hazard	Damage conflict	Congestion
Equipment space			Severe congestion	Safety hazard	Damage conflict	Congestion
Hazard space				No impact	Damage conflict	No impact
Protected space					No impact	Damage
Temporary structures						Severe congestion

Table 2: Spatial-temporal conflict taxonomy (Akinci et al., 2000)

2.2.4 Workspace Conflict Detection Methods

After visualising workspace conflicts, the severity of these conflicts and their overall trend throughout the project lifecycle must be evaluated. To this end, the literature describes several approaches to evaluate the magnitude of workspace conflicts. The critical space-time analysis (CSA) approach that was developed by Dawood & Mallasi (2006) models and quantifies workspace conflicts, and it consists of the following five phases:

- *Phase A*: This phase identifies the main parameters and variables of the CSA, such as the quantities of work, work rate distribution/production rates, the construction activity sequence, and the direction in which a construction activity is executed.
- *Phase B*: Workspaces are assigned to each construction activity, and if one of these workspaces shares the entire or part of the workspace of another activity, then a conflict is registered.
- *Phase C*: The simulation clock in the model is advanced in this phase.
- *Phase D*: This phase reports on the severity of spatial conflicts. This severity is calculated by dividing the total volume of the required space for the construction activities by the total volume of the available space on the construction site. If the resulting score is 1 the space criticality is critical so what is needed is available but there is no tolerance, if the score is above 1 it is more than critical, and below 1 means noncritical.
- *Phase E*: The final phase enables the user to improve the schedule by changing the input variables if there is a spatial conflict.

Dawood & Mallasi (2006) applied this methodology in a real case study (a building project in the United Kingdom) and found that by varying execution patterns, spatial conflicts can be minimised. In their experimental 4D simulation runs, if the execution pattern was west-east the CSA equals 0.83, north-south results in a CSA of 1.08 and the CSA of an east-west execution pattern is 1.21. This illustrates that the execution patterns of construction activities can have a major influence on workspace conflicts. The authors mention that to complement the space criticality scores, a visual representation by using different colours to identify spatial conflicts should help project managers to understand the behaviour of construction activities. Next to that, they add that further work in this area could be the application of this methodology to other project types, e.g. road works.

Risk is typically identified as the product of severity, exposure, and probability (Jannadi & Almishari, 2003). According to Jin et al. (2019, p. 2640), previous studies that focus on risk quantification methods use (a combination of) these three factors, where severity describes the resulting injury from an incident, exposure represents the duration of the hazardous situation and probability (frequency) refers to how often a risk occurs. These authors also show that only a few studies quantify risks based on all three factors; most studies only look at the frequency and severity of risks. This can be illustrated by the method introduced by Shang & Shen (2016), who came up with a 4D BIM-based workspace conflict detection method for evaluating on-site collisions. Their proposed method consists of three steps: (1) 3D workspace representation, (2) Spatial-temporal conflict detection, and (3) 4D Site safety analysis. The first step defines the space usage of on-site activities and categorises them as static workspaces or dynamic workspaces. The second step is to detect the spatial-temporal conflicts between on-site activities, which is done by building a "space-temporal usage matrix" (M_{su}). This matrix represents the space usage of activities in the entire construction stage. M_{su} is a $n \times m$ matrix where n represents the number of space units on the construction site and m the number of time divisions in the construction schedule. The matrix shows the number of objects that use a certain space unit simultaneously. Enlarging the values for n and m can increase the granularity of the model, which improves the precision of results. The final step in this method is to calculate the Site Safety Index (SSI), which is the product of the frequency index (FI) and severity index (SI) of workspace conflicts. In this equation, FI counts the number of spatial conflicts on construction sites and SI measures the magnitude or criticality of these conflicts.

Finally, a risk quantification method that is used by Akinci et al. (2000) and Thabet & Beliveau (1994) is the Conflict Ratio (CR). The CR is calculated for each workspace type by dividing the total conflicting volume by the total required volume (see Figure 9 and Equations 1-3).

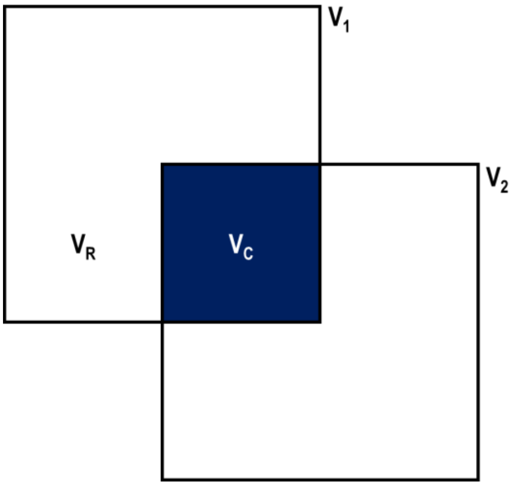


Figure 9: Representation of the total conflicting volume (V_C) and the total required volume (V_R)

[1] $$CR = \frac{V_C}{V_R}$$

[2] $$V_C = V_1 \cap V_2$$

[3] $$V_R = V_1$$

2.3 SPATIAL-TEMPORAL ANALYSIS

2.3.1 Serious Game Engines

To execute the spatial-temporal analysis, a tool has to be found in which a construction simulation can be developed based on a semantically rich (BIM) model. Construction simulation means the method of modelling construction projects to understand their behaviour and to experiment digitally with the model (AbouRizk et al., 2011), which enables researchers and practitioners to test what-if scenarios without having to interfere in the real project (Osorio-Sandoval et al., 2022). According to several studies by Messi et al. (2022a, 2022b), serious game engines offer this possibility and are hence promising tools to address spatial conflict challenges. The application of serious game engines originates in the aviation industry, with the use of Microsoft Flight Simulator for the education of students (Moroney & Moroney, 1991). Later, serious game engines also became more common in the construction industry, for example for safety training purposes such as enhancing electrical safety awareness (Zhao et al., 2009), to improve collaboration and communication in design processes (Van den Berg et al., 2017), and also for simulation-driven visualisations of construction operations (ElNimr & Mohamed, 2011). Messi et al. (2022a, 2022b) use Unity as the game engine for such simulation-driven visualisations, and Section 2.3.2 elaborates in the possible applications of this game engine.

2.3.2 Unity Applications

The first task that has to be executed in the game engine is to create a 4D model, and Messi (2022) describes in his doctoral dissertation in detail how importing an IFC file and loading the work schedule can be done in Unity. After integrating the work schedule with the 3D model, workspaces can be generated in the gaming environment and linked to the work schedule tasks. An example of this is how Price et al. (2021) used Unity to propose a dynamic crane workspace updating method to avoid collisions with objects in the environment during blind lift operations. For this research, the step-by-step description of Messi (2022) on how to generate workspaces is very practical and useful. Another relevant application of Unity is how Weißmann et al. (2023) simulated urban traffic by equipping a virtual environment in Unity with a traffic system consisting of a waypoint network and the associated vehicles. This works as follows: waypoints that represent the traffic network should be manually inserted into the 3D model, and these waypoints should be connected to create a waypoint route. The travel speed of the traffic on every waypoint can be set via the script settings in Unity. Then, the road users are loaded into the waypoint routes where they travel along the predefined route.

2.3.3 Separating Axis Theorem

Checking for overlapping workspace in a simulation model is not straightforward. The main challenge is often that the workspaces in the model are Oriented Bounding Boxes (OBBs) instead of Axis-Aligned Bounding Boxes (AABBs). AABBs are boxes where each side is parallel to one of the coordinate axes (X, Y, and Z), which means they do not rotate with the object but their orientation is always aligned with the coordinate axes (Yang & Laursen, 2007). To calculate the overlap between AABBs, the minimum and maximum values of the boxes along each axis need to be determined since the sides are aligned with the axes, which is a more straightforward method than the one that is required for OBBs. OBBs can rotate freely and their sides are therefore not necessarily parallel to the coordinate axes. As a result, computation and updating of the OBBs in each iteration tends to be much more difficult than with an AABB, and it involves often linear algebra (Yang & Laursen, 2007). One of the most commonly applied methods is the Separating Axis Theorem (SAT), which is a technique to establish whether two convex shapes collide. SAT can only be applied to convex shapes, which is a shape that will only ever have two points of intersection (Newcastle University, 2017). According to SAT, two convex shapes do not collide if and only if there exists at least one separating axis where the orthogonal projections of the shapes on this axis do not intersect (Francisco et al., 2019; Mileff, 2023). Thus, if a line (or plane in 3D) that is drawn between two shapes does not touch either one, they do not intersect (see Figure 10).

The biggest challenge of the SAT algorithm is to identify all possible axes that need to be evaluated (Newcastle University, 2017). If there is an infinite number of axes they cannot all be considered, but in this study we deal with polygonal shapes instead of pure geometrical shapes so the shapes are not curved but made up of straight faces that are connected to form a closed shape. This means that the number of possible separating axes is limited to the number of flat faces and that the normal of each face can be a possible separating axis. Each normal must be evaluated, but once a single separating axis is identified, the algorithm can end early because it has proved that the two objects do not collide. In the worst-case scenario, the number of normals that have to be checked by the algorithm corresponds to the sum of the faces of both objects (which equals 12 in the case of two bounding boxes).

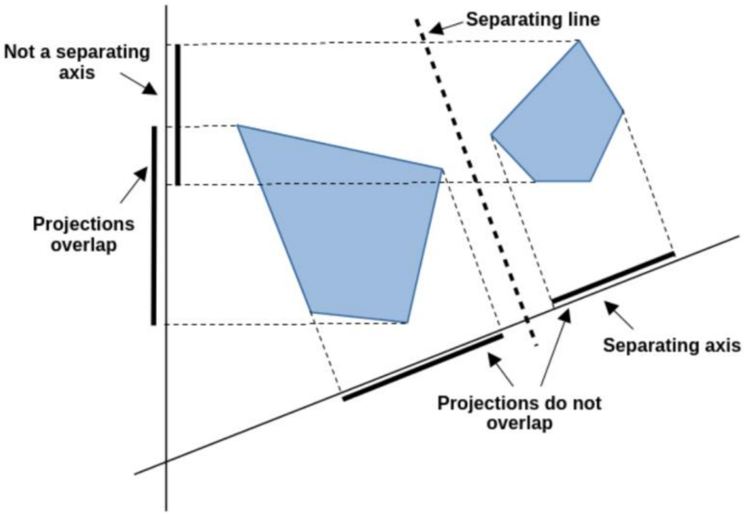


Figure 10: Operation of Separating Axis Theorem (Mileff, 2023)

3

INTERVIEWS

3.1 INTRODUCTION

This chapter aims to explore which sections of work zones or specific construction activities in municipal road construction projects lead to potential collision danger between project resources and road users. To analyse this danger, investigating incident reports as was done by Behm (2005) would be ideal to review as many incidents as possible. Section 1.3 mentioned two studies that used such reports to identify several factors that cause work zone accidents, but the datasets that are used in the analyses of historical crash data often lack detailed information, which makes it difficult to identify if some design choices also contributed to the occurrence of accidents (Debnath et al., 2015). These authors also mention that traffic accidents on road construction sites are often not even reported (which can be confirmed by the author who was not able to find such reports, contrary to accident reports from the building sector), and when we take into account that many risks on a road construction site result in near misses that are also not reported (see Section 1.3) we can conclude that historical crash records do not provide enough information for this research. As an addition to these crash records, Debnath et al. (2015) explored the perceptions of workers regarding work zone hazards and found that the perceived hazards at road construction sites result from driver factors such as speeding and distraction, environmental factors such as weather conditions and limited working spaces, and worker and equipment factors such as lack of appropriate communications and worker ignorance. However, this study did not pay attention to the specific activities and work zone segments that result in hazardous situations, which is the goal of this research. This is done by Kuiper et al. (2007, pp. 61–66), who created an overview of struck-by traffic accidents and near misses but this is not sufficient data for the goal of this research. Hence, additional research to explore the perceptions of workers regarding work zone hazards is required. This is a very valuable research method according to Hadikusumo & Rowlinson (2004), who stated that the experience of construction workers is very important in capturing safety knowledge. They say that safety hazard recognition relies on the workers' experience, and capturing this experience can be done in two ways: by conducting discussions based on drawings and method statements, or by observing the actual construction site. In this study, the second approach is preferred, since the actual representation of the construction site stimulates the interviewees to recall the experience that they have and it results in a quicker understanding of the interviewer.

We will use several case studies as the data collection method in this phase. We will carry out a holistic multiple-case study because according to Yin (2018, p. 54), the evidence from multiple cases is more compelling, and the multiple-case study is therefore regarded as more robust than the single-case study. In this case study, five projects of Roelofs are examined, and this number is chosen because fewer cases would probably not give enough information while analysing more cases is not possible due to the limited available time for this research. Important prerequisites for the selected cases are that the roadways within or close to the project were still used during the project, the type of construction activities had to be different for the cases in order to obtain as much different information from each case as possible, and the projects could not be finished too long ago because otherwise, the involved people would probably have lost certain memories of dangerous situations. Therefore, all selected cases are recently finished or almost finished. The selected cases and some relevant details are shown in Table 3. Case study evidence is then collected by using semi-structured interviews. Semi-structured interviews are suitable for understanding a participant's unique perspective instead of a general understanding of a phenomenon (McGrath et al., 2019). This can be achieved due to the interviewers' possibility to further explore ideas that might come up in the course of the interview (Adeoye-Olatunde & Olenik, 2021). Yin (2018, p. 118) also mentions that case study interviews are guided conversations instead of structured queries, and that although there is a consistent line in the questions of a case study interview, the actual stream of questions is likely to be fluid instead of rigid.

Project location:	Project description:	Participant(s):
Arnhem	Renovating a public artwork and its surrounding environment	Superintendents
Didam	Renewing the centre of the village Didam	Project leader
Haaksbergen	Converting an old provincial road to a distributor road	Superintendent
Oosterbeek	Renovating a district in the village Oosterbeek	Superintendent
Roden	Renewing the centre of the village Roden	Superintendent

Table 3: Selected cases

The interviews were conducted with either the project leader or the superintendent of the case projects because they often have an in-depth understanding of the project and its planning and execution, as well as safety plans and incident reports. As such, they can shed light on the project's potential risks. Moreover, project leaders and superintendents typically have significant experience in the field of road construction. Their expertise can be valuable in assessing the potential dangers and risks associated with the case projects. Some of the interviews are conducted on site, which is the preferred method, but due to practical reasons, some interviews were conducted at the office. The interview questions that were asked to the participants are partially based on the questionnaire that was developed by Kuiper et al. (2007). The interviews are conducted in Dutch, since this is the native language of the interviewees so they feel more confident or are better able to express themselves in Dutch. An English version of the interview questions can be found in Appendix I on page 65. The interviews are firstly focused on identifying construction activities that contributed to work zone related traffic accidents in the specific case project, and secondly on the participants' more general experience with the danger of road users in construction projects. As agreed upon by informed consent, the audio of the interviews is recorded which enables the interviewer to analyse the interviews afterwards. In this analysis, the interviews are anonymised (i.e. the names of the participants cannot be tracked) and the recorded materials are removed after the analysis. The results are described in Section 3.1.1 – 3.1.5, where first a short description of the case project is given, followed by the outcome of the interview with the participant(s) from that case project.

3.1.1 Case 1: Arnhem

In this project, the public artwork "Blauwe Golven" and its surrounding environment were renovated, which included among other things renewing the sewage system, and replacing the pavements of several roads. In this case study, two superintendents are interviewed. The first one was responsible for the phasing and planning of the project, and this interview was conducted at the office because the interviewee was not involved in the execution phase. In the interview, it is stressed by the interviewee that in the planning phase, Roelofs tries to prevent all struck-by hazards but throughout the project, it often turns out that there are more risks than those that were identified previously. In the opinion of the interviewee, the biggest danger related to road traffic is when the same space is shared by road users and construction vehicles. Therefore, he states that a work zone should be completely demarcated from all road users which was not possible in this case due to the demand of the client, the municipality of Arnhem. As a result, it can occur that a shovel picks up a pack of bricks from the depot and brings it to the place where it is needed while crossing a cycle path during this trip. In this specific case, this struck-by danger is a result of the municipality's demand that those paths should be accessible by cyclists during the project. A similar example is when a trench is made and the soil that comes out of the trench cannot be put near the trench due to a lack of space. The interviewee indicates that if the soil is stored near the trench, there is a space required for the soil itself and a hazard space between the soil and the trench because storing an enormous amount of soil directly adjacent to the trench increases the risk that the trench collapses. This space is often not available and in that case, dump trucks have to bring the soil to the depot, and at a later moment from the depot to the trench to fill the trench. These dump trucks often cross a cycling path during these movements. Therefore, Roelofs aims to take the required logistics already in the planning phase into account, by thinking about where all materials should be stored.

An example of a spatial conflict in this project that could lead to struck-by hazards is that the Blauwe Golven includes a lot of bricklaying directly adjacent to the public road, which means that the bricklayers had to use this road partially to execute their tasks. During this operation, one lane of the adjacent road had to be closed partially. For these tasks, the CROW guidelines on the required buffer space between construction activities and road traffic were violated, because these guidelines would require closing the entire road, which was not allowed by the municipality which decided that the road had to be accessible for traffic.

The second interview participant is responsible for the project's execution, which is why this interview is conducted on-site. This interviewee confirms the statement of the previous one that buffer intrusion and sideswipe accidents were a major risk during the bricklaying directly adjacent to the road. Next to that, he identified two major issues. The first one is the behaviour of these road users: most struck-by danger would be eliminated if everyone would listen to the directions on the signs. However, it occurs too often that especially cyclists and pedestrians do not follow the detour but choose the shortest route possible by intruding into the workspace. Sometimes, road users even move a fence or step over it, so the interviewee thinks that the most effective intervention would be a campaign to change the behaviour of road users.

The second large issue is the demand of clients that roads cannot be closed completely, but there is often not enough space on a construction site for the construction activities, for cyclists and pedestrians to pass the work zone, and for a hazard space between those two. The interviewee thinks that a lack of space is always a problem on construction sites. Therefore, he wonders if cyclists should even be allowed to pass the work zone or if it would be better if they took a completely different route. He criticises the Dutch construction industry, where it often happens that one lane of a road is closed for construction activities and the traffic can use the other lane, and after that lane is finished the other lane is closed and traffic can use the first lane. Instead, he prefers a similar approach as the Belgian and German road construction sectors use, namely to close a work zone and the surrounding roads completely. With this approach, the total duration of the construction activities and the corresponding disturbances would be shorter while the safety is higher, although the interviewee acknowledges that this is not possible in all cases and that some roads are too important to be closed completely.

Finally, as an example of a space that is often not thought about, the interviewee indicates that for asphalt paving the end of the paved road is not the end of the work zone. There is also a space required for loading the paver onto a flatbed truck, for example. If there is an intersection at the end of a paved road, the crossing road is necessary for the paving activities as well.

3.1.2 Case 2: Didam

The goal of this project was to turn the centre of Didam into a low-traffic and sustainable centre. The reason why this case is chosen is that it is a good example of the balance between accessibility and safety since the stores have to be sufficiently accessible for the public and for vehicles that supply the stores while these traffic movements are a potential danger for the construction workers. This project was divided into several phases, and during each phase, the streets that were worked on were closed for cars and open for cyclists and pedestrians, but that also resulted in several problems. When the pavement of the road was removed to replace the sewage, pedestrians could still use the sidewalk next to this road but cyclists, moped- and scooter riders had to take a detour. However, they still used the sidewalk without stepping off and continuing on foot, which is also a kind of intrusion because they used a space that they were not allowed to. On the sidewalk, there was not enough space for all these road users, which caused a cyclist to fall against a store window which cracked as a result of this fall.

The interviewee has more examples of intrusion into the work zone. One time, the project team discovered in the morning that one of the construction fences had been moved and that a car had entered the work zone, most likely to avoid the additional travel time resulting from the temporary route. Since this happened at night, no struck-by danger was caused by this incident. Intrusion of the work zone also happens when a construction vehicle enters the work zone which is not realised by other road users who then follow the construction vehicle into the work zone. If these vehicles stay on the public road to unload building materials there is also a spatial conflict between a construction activity and road users, but the interviewee does not consider this as a dangerous situation, because in practice this can always be regulated very well through traffic controllers. Another spatial conflict that is mentioned by the interviewee involves a general situation which is not related to this case project, but during asphalt paving, there are always several trucks waiting in a queue, and sometimes there is not enough space for these trucks so they are forced to use the traffic zone.

A more serious struck-by hazard is when construction workers have to cross travel lanes, and the interviewee also has some examples of this. Usually, the activity sequence for renovating a street is removing the road pavement, removing the sidewalks, constructing the new sidewalk, and finishing by paving the street. In this case project, Roelofs experienced a lot of pressure from the municipality to open the road as soon as possible for traffic, which is why they decided to change the work sequence and pave the road first to make it accessible for cars and to construct the sidewalks afterwards. These sidewalks were quite wide so there was enough working space on the sidewalk, which means that the workers did not have to use the road for the construction activities. However, they had to cross the already opened road quite often for the supply of materials, which resulted in struck-by danger. A similar situation occurred when the pavement of another sidewalk in this project had to be redone, but the bricks for this sidewalk were placed on the opposite side of the road while the road was already open for traffic. The worker had to cross this road several times, so clearly the struck-by danger of road traffic was not thought about when the bricks were placed. These examples show that choosing the location of the depot is very important. The interviewee also indicates that in the design phase of construction projects, the workspaces required for maintenance should also be taken into account. For example, if there is greenery implemented in the middle of a road, the road has to be used for maintaining the greenery which leads to spatial conflicts with the road traffic.

3.1.3 Case 3: Haaksbergen

After the new provincial road N18 has been opened on the north side of the Dutch town Haaksbergen, the old N18 no longer serves a function for through traffic. As a result, there has been a sharp decrease in the use of this road by motorised traffic, and it is only used to access Haaksbergen. Therefore, the function of the old N18 is in this construction project adapted to a distributor road, and this adjustment of function includes a changed design to align the function, design, and use of the road. Some construction activities of this project are executing the required asphalt maintenance and implementing the necessary traffic adjustments.

From the selected cases, this project is unique in the sense that no traffic is allowed near the work zone. Only very rarely does a cyclist or pedestrian intrude into the work zone in an attempt to find a shorter route. The interviewee mentions that an advantage of closing a work zone completely is that it is much easier to store building materials close to the place where they will be used. From other projects, the interviewee has the experience that if the accessibility for road users increases, the safety decreases. An example of this is that if road construction happens on one side of the road while traffic can use the other lane. This way, road users travel adjacent to the work zone which increases the struck-by danger, mainly because construction vehicles often have to leave the work zone and enter the traffic zone. Some advice from the interviewee for construction planners is to think about the required equipment for a project and how much space they need, which determines together with the hazard spaces the borders of the work zone. He thinks that this will show in some cases that there is no space left for traffic to pass the work zone. Too often, designers promise something to a client that is not possible in practice, and projects are often designed without the input of a superintendent to assess the constructability of the project, especially with regard to the required space. This is the reason why the interviewee likes a *bouwteam* as the contract form is that this enables him to participate in the design process. The interviewee's experience is that clients often exert pressure to keep a road accessible for road users during a construction project. Still, he also expects that if a spatial planning that indicates the lack of space for road users to pass the work zone is shown to the client, they can be convinced to close the work zone completely.

With regard to the hazard spaces, they are often taken into account in the design but in practice, these spaces are sometimes used for other purposes as well. Examples of spaces that are often disregarded in the design phase are that sewer inspections do not just require a camera, but multiple trucks are needed to clean and inspect the sewer which occupies a lot of space. With regard to asphalt paving, spaces that are not taken into account are the space for workers who walk next to the asphalt paver, a space for the storage of the trailers that transport the paver and rollers, and for asphalt trucks to wait in a queue until they can unload their asphalt, the space for asphalt trucks to turn around before they can go backwards to the paver, and the space for rollers who have to leave the paved road completely to compact the joint between the new and old asphalt properly. The latter two are especially a problem if there is an intersection at the end of the work zone.

3.1.4 Case 4: Oosterbeek

The thirteen streets and sewer systems of a residential area in Oosterbeek are renovated in this project. The activities include removing the asphalt pavement, replacing the sewers, and paving the streets again with bricks. These roads are renovated in different phases, and the roads that are under construction are closed to cars and cyclists. To avoid intrusion into the work zone, this project team uses concrete blocks with reflective strips as a barrier to prevent that people can move the barrier themselves. There is a sidewalk for pedestrians next to the work zone. This sidewalk has to be at least 90 cm wide according to the CROW guidelines, and this sidewalk is separated from the work zone through wire netting instead of the conventional construction fences. This choice is made because these conventional fences have a foot that is approximately 60 cm wide, and wire nets are much smaller which saves some essential space in the small streets of Oosterbeek. A disadvantage of wire nets is that this makes it easier for construction workers to step over these barriers and enter the traffic zone. An example of why this happens is if there is a crane in the work zone and no space to go around this crane, construction workers sometimes step over the barrier to go around to crane. Due to this lack of space on the construction site, there is also no opportunity to store materials in the work zone, which is why there is a depot a few kilometres from the project location. The interviewee admits that these transportation movements can result in struck-by danger because the construction vehicles often leave and enter the work zone, which is why a traffic controller is appointed to reduce this danger.

According to the interviewee, a workspace that should be thought more about in the design phase is the space that is required for the maintenance of greenery between travel lanes, because this maintenance results in a moving work zone on a road that is also being used by cars, thereby increasing struck-by danger. A final advice from this interviewee is that if a client requires that road users should be able to pass a work zone and there is not enough space for these road users based on the CROW guidelines, designers should not compromise these guidelines but look in consultation with the client if it is possible to let the road users take a detour. In the interviewee's opinion, these guidelines are often not sacred among designers, he stresses that designers should take the guidelines for sidewalk dimensions and hazard spaces more into account.

3.1.5 Case 5: Roden

The goals of this project were to make the centre of Roden more attractive by adding more greenery and facilitating more life on the streets (for example, through more terraces, less parking chaos, etc.), and to make the centre climate-proof by renewing the sewerage system in order to have sufficient water storage. The main activities of this consisted of replacing the (asphalt) pavements, foundations, and sewers. These activities started in June 2021 and the project was completed in August 2023. The total sewer system, consisting of a sewer for wastewater and one for rainwater, is 320 meters long and the construction of these sewers was executed by several crews: the first one was for removing the existing pavement, excavating the required trench, and disposing the excavated soil into a depot using dump trucks. Approximately once a week, a crane lifted the culverts into the trench, after which another crew started to fill the trench with the soil from the depot and to pave the street again. Thus, the construction of the sewer system was a continuous process where one crew was always breaking up the road and another crew always worked on closing the road again. This way, there are always two locations where construction vehicles interfere with public road users: the place where the dump trucks leave the project location to bring soil to the depot, and the place on the other side of the project where dump trucks enter the work zone with soil that they retrieved from the depot. According to the interviewee, the public does not expect a construction vehicle to leave a work zone, which can result in hazardous situations.

Some other key learning points from this interview about intrusion danger are that the interviewee indicated that if they did not close the construction fences completely, cyclists would immediately enter the work zone in an attempt to find a shorter route. This resulted from the disturbances that were caused by the project, the accessibility of the centre was drastically reduced during the project. So, it was not the danger of the project that Roelofs received complaints about, but rather about how much inconvenience the project caused. Next, the interviewee mentioned as an example of dangers for road users resulting from activities the milling of asphalt, because if the buffer space between the milling machine and road traffic is not big enough the wind can blow asphalt grains against the cars, cyclists, and pedestrians. Finally, the interviewee indicated that the depot of a project is often not large enough, and as a result, materials are then stored in places where that is not supposed to happen. An example of this is that buffer spaces that are intended to keep a safe distance between workers and traffic are (partially) used for material storage if there is a lack of space on site. Even though the CROW guidelines for buffer spaces are always taken into account in the planning phase, these rules are sometimes violated when there is a lack of space.

3.2 ANALYSIS OF THE CASE STUDIES

For the analysis of the case studies, Figure 3 (page 3) will be used. This section discusses for all eight categories of struck-by danger that are mentioned in Figure 3 if they are recognised by the interviewees. It is important to note that these categories were not explicitly introduced to the interviewees, because in that case, they would probably recognise most categories as dangerous situations. Instead, it was tried to let the interviewees come up with these dangers themselves.

3.2.1 Road workers enter the traffic zone

The first category is when construction vehicles enter or leave the work zone. This was mentioned in several cases: the interviewee from case 3 has the general experience that if one side of the road is opened during construction operations on the other side of the road, construction vehicles often have to leave the work zone and enter the traffic zone or vice versa. In case 4 and case 5, dump trucks had to transport a huge amount of soil from the work zone to the depot which was located a few kilometres further, and this soil had to be brought back to the work zone later in the project. Thus, there were many occasions in these projects where construction vehicles had to enter or leave the work zone. Construction workers who cross travel lanes happened in the first two cases. Examples from the first case are that a shovel picks up a pack of bricks from the depot and brings it to the place where it is needed while crossing a cycle path during this trip. A similar example is when a trench is made and the soil that comes out of the trench cannot be put near the trench due to a lack of space, and dump trucks have to bring the soil to the depot and at a later moment from the depot to the trench to fill the trench. These dump trucks often cross a cycling path during these movements. Case 2 also contains two examples where construction workers had to cross travel lanes for the supply of materials. The last category of road workers who enter the traffic zone is when they work outside the defined work zone. The interviewee from case 4 was the only one who explicitly mentioned this danger, he says that it can occur when there is not enough space in a work zone for workers to move around and that they step over a barrier in order to get to another place in the work zone.

3.2.2 Road users enter the work zone

An example of a full intrusion is shown in case 2, where it sometimes happens that a construction vehicle enters the work zone which is not realised by other road users who then follow the construction vehicle into the work zone. Buffer intrusion and sideswipe accidents were especially a danger in case 1, where bricklaying was executed directly adjacent to the road, which means that the bricklayers had to use this road partially in order to execute their tasks. Moving work zone intrusion was not a danger in one of the investigated cases, but two interviewees (from case 2 and case 4) did mention it as a general danger. They said that in the design phase of construction projects, the workspaces required for maintenance should also be taken into account. For example, if there is greenery implemented in the middle of a road, the road has to be used for maintaining the greenery and such maintenance activities always include the danger of moving work zone intrusion. Access intrusion, on the other hand, was mentioned in all five cases. All interviewees experience in their case project that cars, cyclists and/or pedestrians enter the work zone in an attempt to find a shorter route or to avoid the temporary route. Finally, a form of debris intrusion was mentioned by the interviewee from case 5. He considers the milling of asphalt as a danger for road users, because if the buffer space between the milling machine and road traffic is not big enough the wind can blow asphalt grains against the cars, cyclists, and pedestrians.

3.2.3 Additional workspaces

In the interviews, it was also asked if the participants knew some spaces that are not taken into account in the planning phase, but that can result in dangers for road users. Most of the mentioned examples are related to asphalt paving. One of the interview participants from case 1 indicates that for asphalt paving the end of the paved road is not the end of the work zone. There is also a space required for loading the paver onto a flatbed truck, for example. If there is an intersection at the end of a paved road, the crossing road is necessary for paving activities as well. The same example was mentioned by the interviewee from case 3, who adds that this space is also required for asphalt trucks to turn around before they can go backwards to the paver, and for rollers who have to leave the paved road completely to compact the joint between the new and old asphalt properly. From these examples, it can be concluded that there is often not sufficient longitudinal buffer space (see Figure 2) for asphalt paving operations. The interviewee from case 3 mentioned other examples of spaces related to asphalt paving, such as the space for workers who walk next to the asphalt paver, a space for the storage of the trailers that transport the paver and rollers, and a space for asphalt trucks to wait in a queue until they can unload their asphalt. The last one is mentioned by the interviewee from case 2 as well, who also recognises the space for vehicles that stay on the public road to unload building materials, and a final example of the interviewee from case 3 is that for sewer inspection activities, not just an inspection camera is required but multiple trucks are needed to clean and inspect the sewer which occupies a lot of space.

3.2.4 Hazard spaces

The required hazard spaces that result from the CROW guidelines are not sacred, is a conclusion from the interviews. One of the interviewees said that for the bricklaying directly adjacent to a public road these guidelines were violated because the municipality mandated that the road had to be accessible for traffic. The interviewee from case 3 indicated that the hazard spaces are often taken into account in the design but in practice, these spaces are sometimes used for other purposes as well. In the experience of the interviewee from case 4, the CROW guidelines are often neglected in construction projects. This is confirmed in case 5: in this interview, it turned out that as a result of a lack of space on a construction site, hazard spaces are sometimes used for other purposes such as material storage.

3.2.5 Concluding remarks

Table 4 summarises Section 3.2.1 – 3.2.4 and it shows in descending order that all categories of struck-by danger that were identified in Section 1.3 are recognised by the participants of the semi-structured interviews. As a solution to the identified hazards, almost all interviewees stated that a work zone should be completely demarcated from all road users. In the first case, one of the participants mentioned that the total duration of the construction activities and the corresponding disturbances would be much shorter while the safety would be higher, although he acknowledges that these roads are too important to be closed completely which is why the client, the municipality of Arnhem, did not allow this. Other interviewees did not explicitly mention this solution, but it can be assumed that they would all agree with it. Case 3 is an example of a project where the work zone is completely demarcated, and the interview participant from this case describes how a project can be improved if no traffic is allowed near the work zone. This participant also expects that if a spatial planning that indicates the lack of space for road users to pass the work zone is shown to the client, they can be convinced to close the work zone completely. Furthermore, one of the most remarkable results from the interviews is how often the CROW guidelines concerning hazard spaces and mandatory traffic spaces are violated. According to the interviewee from case 4, this should not be allowed and traffic should take a detour if the required traffic space cannot be realised.

Thus, the input from the interviews for the spatial-temporal analysis consists of the following key points:

1. Since access intrusion was mentioned by every interviewee, the to-be-developed tool should contain an option to predict the behaviour of road users, i.e. road users should have the option in the simulation to leave the predefined path and intrude the work zone in an attempt to find a shorter route.
2. Attention should be paid to the hazard spaces of construction activities because these spaces are often neglected due to a lack of space, which is why the spatial-temporal analysis should easily indicate if these guidelines are maintained.
3. Next to static workspaces, the collision detection tool should contain the option to model dynamic workspaces, because such moving workspaces are also a major risk based on the interviews (e.g. caused by construction vehicles that enter or leave the work zone).

	Case 1:	Case 2:	Case 3:	Case 4:	Case 5:
Access intrusion	✓	✓	✓	✓	✓
Neglection of the required hazard spaces	✓		✓	✓	✓
Construction vehicles enter/leave the work zone			✓	✓	✓
Construction workers cross travel lanes	✓	✓			
Moving work zone intrusion		✓		✓	
Buffer intrusion	✓				
Full intrusion		✓			
Debris intrusion					✓
Construction workers work outside the work zone				✓	

Table 4: The occurrence of the causes for struck-by accidents in each case

4

CONFLICT DETECTION FRAMEWORK

4.1 INTRODUCTION

This chapter presents a novel methodology that integrates the BIM model of a construction project, its work schedule, and the (temporary) traffic routes during the project with a spatial conflict simulator. The proposed methodology consists of four sequential steps: building model preparation, traffic simulation, workspace generation and allocation, and site safety assessment. These steps are explained in Section 4.2 – Section 4.5 respectively, and the framework in Figure 11 gives an overview of this approach.

4.2 BUILDING MODEL PREPARATION

The building model preparation stage starts with preparing the building model of a project. The input for this activity is a 3D BIM model, and the preparation consists for example of removing parts of the model that are not relevant for the collision detection so that the model is not unnecessarily large. The next step is to extend this design by adding the existing infrastructure because at the beginning of the project, traffic still uses the old roads so these roads should be included in the model. It would be the most convenient to create a model with two layers, with the newly designed situation above the old situation. The next step is then to create a 4D model by adding the project planning to the 3D model. As explained in Section 2.1.2, the unit of time in this project planning should ideally range from hours to minutes in order to follow the movements of equipment and resources. This duration should be retrieved from the project planning, but the project planning often contains estimated durations of construction activities. However, the duration of an activity is not fixed, but subject to the dynamic nature of a construction project. Failure or success in achieving the planned duration for each construction activity depends on various parameters, such as logistics delay, decrease in productivity of workers, and addition of work (Al Ameri & Nasaruddin, 2020). Therefore, the fixed time durations from the project planning should be turned into stochastic durations, by selecting a maximum percentage that an activity duration can decrease, and a maximum percentage that an activity duration can increase. This way, a stochastic 4D model is created by randomly choosing an activity duration between a selected upper- and lower bound for each construction activity, and as a result each simulation run is different. These construction tasks have to be linked to an element in the 3D model (Bourlon & Boton, 2019; Mezrag & Boton, 2021), so one or multiple elements from the model need to be assigned to each activity in the planning. Based on this link, it can be determined for each element if it should be visible at a certain time in the simulation. If the resulting 4D model is simulated, the entire new situation is not visible at the beginning of the simulation; only the old situation (the bottom layer) can be seen. Then, during each activity, one or multiple elements from the old situation can disappear and one or multiple elements from the new situation can appear in the simulation. At the end of the simulation, all elements of the new situation are created and only the new situation is visible at that moment.

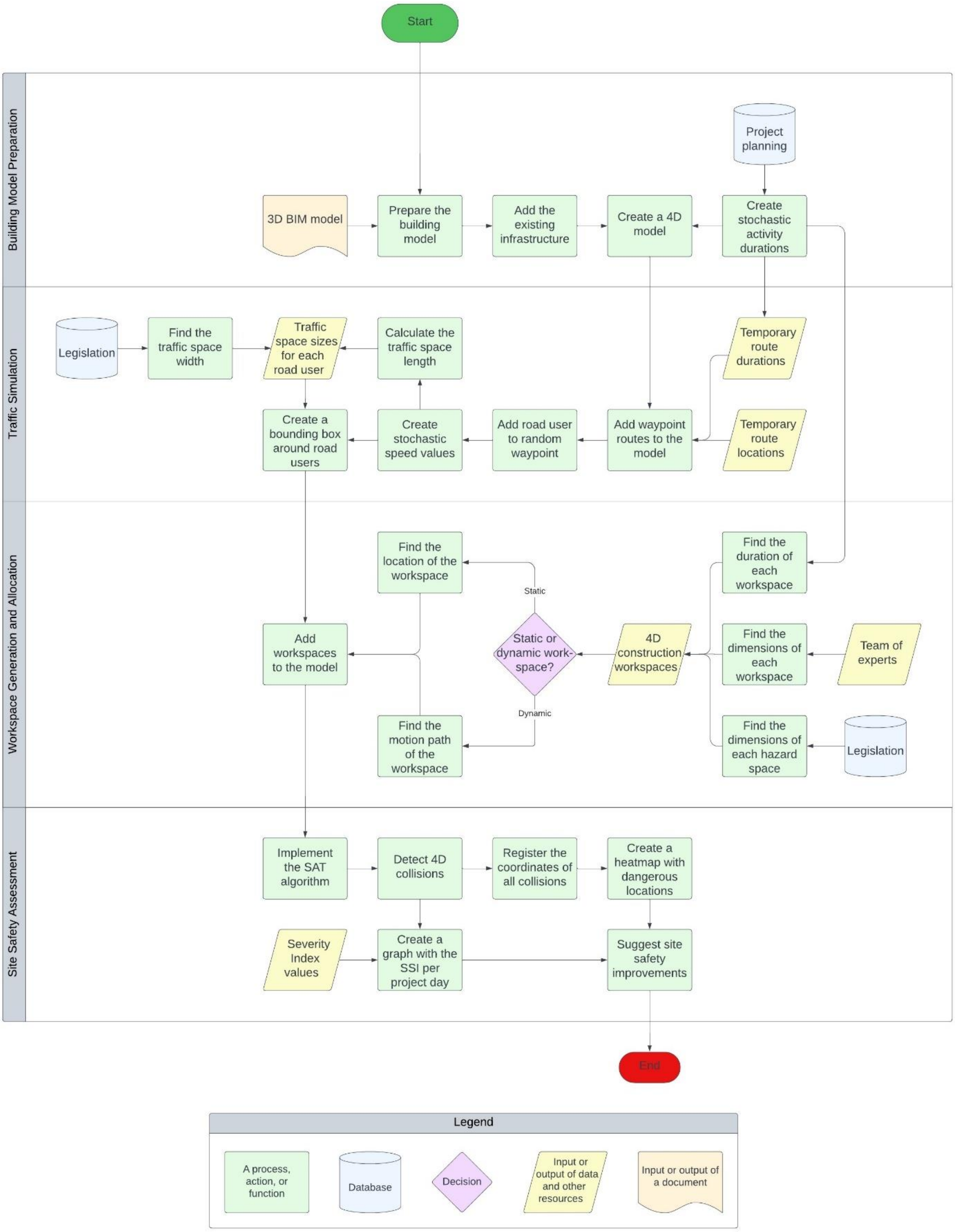


Figure 11: Conflict detection framework

4.3 TRAFFIC SIMULATION

The first step for the traffic simulation is to add the temporary routes with waypoints. The input for these waypoint routes includes information about the type of road users that are involved in the project (e.g. cars, trucks, buses, cyclists, pedestrians, etc.), the location of the temporary routes (which roads are used for each traffic type), and the duration of each temporary route (based on the project planning). The latter is important because in some projects, the traffic routes change several times. The next stap is to add the road users to the waypoint routes, and they must start at random waypoints, in order to create a stochastic distance between the road users. An additional stochastic element that could be added to this traffic simulation model is the number of road users on a route. Then, a stochastic speed is assigned to each road user, and this speed is calculated similar to how the deviation in construction activity durations is calculated. So, the average speed of a road user should be entered in the simulation model, as well as the maximum percentage that this speed can decrease and the maximum percentage that speed can increase. Next, a bounding box is added around each road user to indicate how much space the road user requires. Two factors influence the size of this bounding box: its width depends on governmental regulations which contain the minimum road width that should be available for a certain type of road user, and the length of the bounding box depends on the braking distance of the road user that is a function of its speed. Based on all this information, a 4D model is created in which the traffic is simulated, and the locations of the temporary traffic routes can even change several times.

4.4 WORKSPACE GENERATION AND ALLOCATION

This stage adds workspaces to the simulation model. For all workspaces except for hazard spaces, input from a team of experts is required for the size and location of these workspaces because this depends on the construction activity that they are associated with. This is different for hazard spaces: their size and location depend on the prescribed legislation (Section 0). Since each space belongs to one or multiple construction activities, they should only be visible during these activities in the simulation, which is why the project planning serves as the input for the duration of each workspace. The combination of workspace dimension and duration results can generate the workspaces, but for its allocation, the decision has to be made if a workspace is static or dynamic. If a workspace is static, its location has to be determined, and for dynamic workspaces it has to be decided what their motion path is. If all workspaces with their attached information are added to the traffic simulation model of the previous step, a spatial conflict detection model is created which enables the last step: to assess the safety of the construction site.

4.5 SITE SAFETY ASSESSMENT

In the final step, the conflicts are detected and quantified. For the detection of conflicts, the SAT should be used (Section 2.3.3). After all conflicts are detected utilising the SAT, the overall safety of the construction site should be assessed which is done with the risk quantification method that is explained in the remainder of this section. This method is based on the assumption that on-site risks are the product of severity and probability, where severity is the effect of the risk and probability indicates how often the risk occurs (Baradan & Usmen, 2006). First, all possible collision types have to be identified. A collision type consists of the involved road user and the involved workspace type, so the number of collision types equals the number of road user types multiplied by the number of workspace types. Each collision type should be given a severity score, which should represent its relative danger compared to other collision types. Then, the overall site risk can be determined by running the simulation N number of times and using Equation 4:

$$SSI = \sum_{n=1}^{N} \sum_{i=0}^{k} SI_i * \frac{F_{i,n}}{N} \qquad [4]$$

In this equation, *SSI* is the resulting site safety index, *N* is the number of simulation runs, *k* is the number of collision types, SI_i is the severity index of collision type *i*, and $F_{i,n}$ is a Boolean value which equals 0 if collision type *i* did not occur in simulation run *n*, and 1 if collision type *i* did occur in simulation run *n*. The calculation goes as follows: for each simulation run, the formula loops through all collision types, and multiplies its severity index by the probability of its occurrence. The probability that collision type *i* occurs in a single simulation run is calculated by dividing $F_{i,n}$ by *N*, because the formula also includes a summation over all summation runs. For example, if collision type *i* occurs 2 times, the summation will eventually include S_i * $^2/_{10}$ which is the severity of collision type *i* multiplied by its probability. The SSI should be calculated for each construction activity independently, which results in a safety score for each construction activity and a graph with the activities on the x-axis and the site safety scores on the y-axis. After this is done, the final step of the site safety assessment is that for each collision, the coordinates of the road user that was involved in the collision is registered. Based on these coordinates, a heatmap can be generated that shows the most dangerous locations of a construction site.

5

SPATIAL-TEMPORAL ANALYSIS

5.1 INTRODUCTION

In this chapter, the methodology that was proposed in Chapter 4 is applied to a real project of Roelofs. To achieve this, a system architecture is defined in Section 5.2 which shows the approach that is used for the spatial-temporal analysis in this case study. Next, Section 5.3 is an introduction to the case project itself, and the remainder of this chapter is a step-by-step guide for loading the BIM model (Section 5.4.1) and the work schedule (Section 5.4.2) within Unity, simulating the traffic flow (Section 5.5), generating the main workspaces (Section 5.6), and finally detecting spatial conflicts (Section 5.7).

5.2 SYSTEM ARCHITECTURE

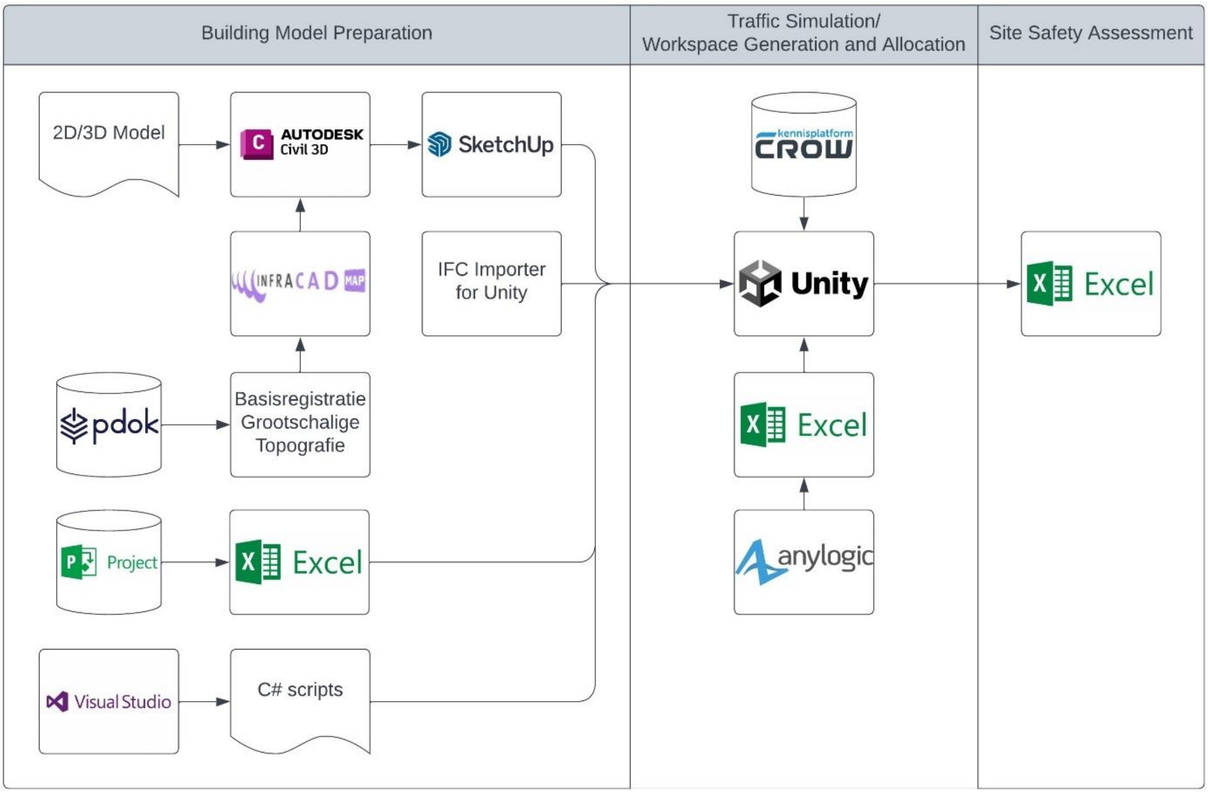


Figure 12: The proposed system architecture with the implementation of the proposed framework

Figure 12 shows the proposed system architecture, which shows how the framework from Figure 11 is implemented in this case study by giving an overview of the information flow between the used software tools. The first step in the framework is to choose and prepare a BIM model, so the first required software tool is the one that Roelofs uses for its BIM models, which is Autodesk Civil 3D. The prerequisites for the used BIM model are that it contains the surrounding public roads that are still used during the construction phase, in order to model workspace conflicts with these roads. However, this is not the standard because it often appears to be insignificant for the work that has to be carried out. There are several ways to add the existing infrastructure, for example by integrating a digital map of the Netherlands such as OpenStreetMap (OpenStreetMap, n.d.) or the *Basisregistratie Grootschalige Topografie* (BGT) with the 3D model. In this research, the BGT is chosen which consists of a large number of digital area maps that all fit neatly together (BZK, n.d.). Several authorities such as ministries, provinces, water boards and municipalities are responsible for maintaining information about their own areas. The resulting map is accurate to within 20 centimetres and it contains many details about the layout of the physical environment, including objects such as buildings, roads, railways, waterways, and greenery. To import this map into a 3D design, InfraCAD Map was used as an add-in for AutoCAD Civil 3D. With InfraCAD Map, it is possible to select a specific area, after which the required data is downloaded from the platform *Publieke Dienstverlening Op de Kaart* (PDOK) and imported into Civil 3D.

In this study, Unity was used as the game engine because this game engine contains all applications that are required for this research (see Section 2.3.2 for an overview of the possible applications of the game engine), and Unity is free for students enrolled at accredited educational institutions (Unity, n.d.). Unity has an in-house IFC importer to import BIM models into the gaming environment, but it turned out that an IFC file could not be imported directly from Civil 3D to Unity, which is why SketchUp is used as a "pipeline" to make the exchange of data possible. Next, Unity also offers the possibility to import construction schedules in CSV format using a C# script (all scripts in this study are written by the author unless explicitly mentioned otherwise). These scripts are programmed in the Visual Studio 2022 environment, and the temporal data for the 4D model can be obtained from the construction schedule of the case project in Microsoft Project. This schedule contains the task id, task description, required previous tasks, the task duration, and its start and end dates. After creating the 4D model by integrating the work schedule with the 3D model, the traffic can be simulated and workspaces can be generated in Unity. The input for these workspaces consists of the interview results, the CROW guidelines concerning hazard spaces, and additional information from experts at Roelofs. To identify spatial conflicts during the simulation, they can be represented visually by changing the colour of the spatial intersection and by printing a message that reports the conflicting workspaces to the user. Moreover, the list with all spatial conflicts is written to an Excel file, which allows the user to analyse the reported data.

Most workspaces in this case study are macro-level workspaces which give a more generalised view of the construction project where the focus is on the overall layout, structure, and major components of the construction site. Therefore, these workspaces are modelled as static workspaces. However, for an asphalt paving activity in this case project, the workspaces will be defined on a micro-level, which zooms in on specific details of the activity, including a more detailed analysis of individual workflows and construction elements, such as workers, machinery, materials, and their interactions. This results in dynamic workspaces, and this level of detail allows for a more realistic representation of the construction activity. The input for these dynamic workspaces is an AnyLogic simulation model of the compaction process that was developed by Dalence et al. (2021). This simulation model generates the coordinates of a roller based on several input variables such as the road dimensions. These coordinates can be exported to an Excel file and loaded into Unity in order to have realistic roller paths in Unity.

5.3 CASE INTRODUCTION

5.3.1 Project Description

The project that is chosen for this case study is the Blauwe Golven in the city of Arnhem ("Blue Waves", see Section 3.1.1). The reason behind this choice is that this project includes a huge variety of construction activities so it is possible to show for many activities how they impact struck-by danger, and since the project location is in the centre of Arnhem, it is a busy spot with many different road users near the work zone such as cars, cyclists, and pedestrians. Therefore, this is a suitable case study for this research. The Blauwe Golven is the largest outdoor artwork in the Netherlands (Archive of Destruction, n.d.). It was designed by artist Peter Struycken and completed in 1977, and its undulating pattern of white and blue paving stones functions as a parking area. It is right underneath the Nelson Mandela Bridge that crosses the Rhine River in central Arnhem, so it serves as the western entrance to Arnhem and is of major importance for the accessibility of the city centre. Between 2022 and 2024, Roelofs will work on the renovation of the Blauwe Golven and its surrounding environment (Roelofsgroep, n.d.-c). They will execute this project in a *bouwteam* together with the artist, the architect and the municipality, in order to create an optimal design together (see Figure 13 and Figure 14 for an overview of the old and new situation, respectively). The main goals of this project are restoring the environmental artwork Blauwe Golven, improving its visual appearance and usability, and transforming the Oude Kraan into a promenade with an integrated bicycle street.

Figure 13: Old situation (Google Earth Pro, 2021)

Figure 14: New situation (Roelofsgroep, n.d.-b)

The time that is available for this research is too short for simulating all workspaces of the entire project, so the spatial-temporal analysis has to be limited to a specific area of the project. The area that is chosen is located on the north side of the project: it involves the reconstruction of the Oude Kraan. The Oude Kraan is a combination of a road that can be used by cars to access the parking places on the Blauwe Golven, a bicycle highway and a promenade. Next to the construction of these three roads, all subsurface utilities such as the sewage system, water pipes and telecommunication cables are also being renovated. A difficulty of this area is that the buildings are directly adjacent to the promenade of the Oude Kraan: these buildings have to be accessible during construction so the work zone cannot be completely closed, and the presence of buildings next to a work zone limits the space that can be used for the work zone. The challenge of surrounding buildings for work zones was previously identified by Gan & Ge (2023) and mentioned in Section 1.3. Thus, the presence of different kinds of road users, the huge variety of construction activities and the lack of space make this part of the project interesting for a spatial-temporal analysis.

5.3.2 Project planning

Figure 15: Cross-section of the old situation of the Oude Kraan

Figure 16: Cross-section of the new situation of the Oude Kraan

Figure 15 and Figure 16 show the cross-sections of respectively the old and new situations of the Oude Kraan, with consecutively the Blauwe Golven (1), the access road for cars (2), a wadi that collects rainwater and infiltrates it into the ground (3), the bicycle highway (4), the promenade (5) and the adjacent buildings (6). After comparing these two cross-sections, it can be seen that all functionalities are preserved in the new situation, but the dimensions of the different elements have changed.

Nr.:	Activity:	Duration (weeks):
1	Removing the pavement of the old cycling path	1
2	Construction of a new sewage system underneath the cycling path	2
3	Removing the old sewage system underneath the roadway	1
4	Pavement with bricks of the new roadway	2
5	Removing the pavement of the old roadway	1
6	Creating the greenery	1
7	Asphalt paving of the new bicycle highway	2
8	Remove old promenade	1
9	Pavement with bricks of the promenade	2

Table 5: Project planning of the Oude Kraan

Table 5 shows the nine main construction activities and their durations that can be identified for the Oude Kraan. Over the course of this project, cars always use the roadway (nr. 2 in Figure 15), but the locations of the temporary routes for cyclists and pedestrians change several times. During activities 1 and 2, cyclists use the roadway. During activities 3 and 4, cyclists can still use the part of the roadway that is not part of the newly constructed roadway, but this road was closed for cars during these activities which means that the parking places on the Blauwe Golven are not accessible. During activities 5-7, cyclists and cars can use the new roadway (nr. 2 in Figure 16). Finally, during activity 8, pedestrians use the newly constructed bicycle highway (nr. 4 in Figure 16), while cyclists still use the roadway instead of the bicycle highway, because the latter has to be used for material storage and equipment movements as well so there is not enough space for both cyclists and pedestrians. Table 6 summarises all temporary routes of each traffic type.

Activities:	Cars:	Cyclists:	Pedestrians:
1,2	Old roadway	Old roadway	Old promenade
3,4	N/A	Old roadway	Old promenade
5,6,7	New roadway	New roadway	Old promenade
8,9	New roadway	New roadway	New bicycle highway

Table 6: All temporary route situations

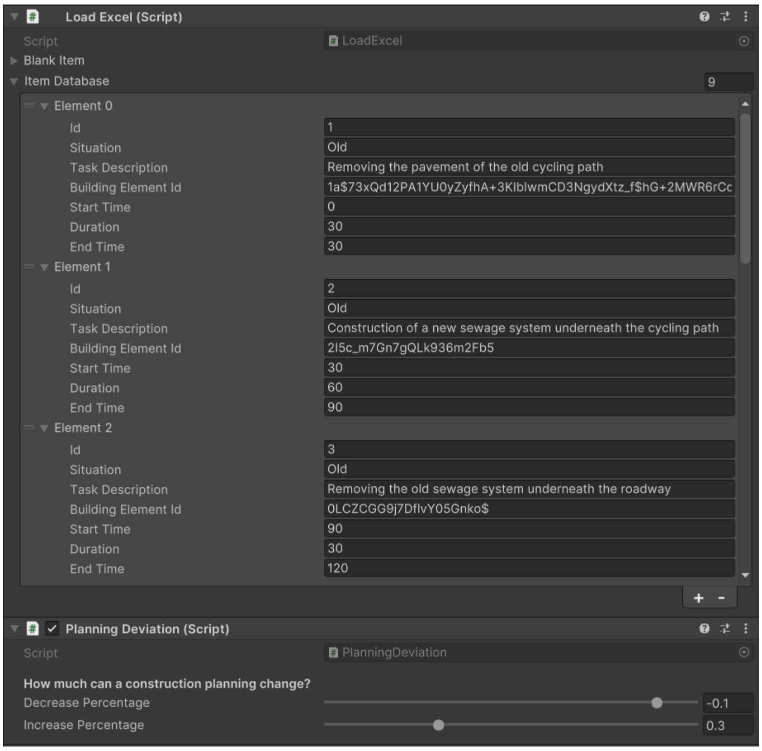
5.4 BUILDING MODEL PREPARATION

5.4.1 Surrounding environment

For the Blauwe Golven, several designs are available. Roelofs created a 3D design of the undulating pattern of white and blue paving stones. However, the design of the other parts of the project (such as the Oude Kraan) is not included in this model. Therefore, we chose to use the 2D design of the Blauwe Golven in which every part of the project is considered, but since only the Oude Kraan is relevant for this research we took that part of the model as our MVD. Several elements are added to this MVD through the BGT: the buildings directly adjacent to the promenade of the Oude Kraan, and the elements of the old situation. The map of the old situation is placed underneath the 2D design of the new situation, which results in a 2D model with two layers (this methodology is explained in Section 4.2). However, the elements in the resulting model were hatches instead of 3D solids. A hatch fills an area with a hatch pattern, solid fill, or gradient fill (Autodesk, n.d.). This means that a hatch indicates certain types of information or materials in a drawing, so hatches only represent an object but are not an object itself and are also not recognised by Unity as an object after importing the IFC file of this drawing. To solve this problem, every hatch in the drawing had to be converted into a 3D solid through the "Extrude" command in Civil 3D. The resulting 3D model of the Oude Kraan can be seen in Figure 34 in Appendix II.

5.4.2 4D modelling

In order to define the 4D model, the work schedule from Table 5 must be formatted into a CSV file and placed in the "Resources" folder. In this CSV file, the duration of each activity had to be changed into a number that is suitable for a simulation run, and it was chosen that one actual week of construction work is represented by 30 seconds in the simulation. Next, the "Load Excel" script, attached to the "Databases" game object, enables this step. The Tools menu in the Toolbar at the top of the Unity Editor contains a button to read the schedule, after which the Id, Situation, Task Description, Building Element ID, Start Time, Duration and End Time of each element in the Item Database is filled with the right information (see Figure 17).



Load Excel (Script)

Script: LoadExcel

Blank Item

Item Database: 9

Element 0

Id: 1

Situation: Old

Task Description: Removing the pavement of the old cycling path

Building Element Id: 1a$73xQd12PA1YU0yZyfhA+3KIbIwmCD3NgydXtz_f$hG+2MWR6rCc

Start Time: 0

Duration: 30

End Time: 30

Element 1

Id: 2

Situation: Old

Task Description: Construction of a new sewage system underneath the cycling path

Building Element Id: 2I5c_m7Gn7gQLk936m2Fb5

Start Time: 30

Duration: 60

End Time: 90

Element 2

Id: 3

Situation: Old

Task Description: Removing the old sewage system underneath the roadway

Building Element Id: 0LCZCGG9j7DfIvY05Gnko$

Start Time: 90

Duration: 30

End Time: 120

Planning Deviation (Script)

Script: PlanningDeviation

How much can a construction planning change?

Decrease Percentage: -0.1

Increase Percentage: 0.3

Figure 17: Loading the work schedule

The field Building Element ID shows the id's of all building elements that are part of a certain activity, and the Situation field indicates if an activity is linked to a building element of the old situation (bottom layer) or the new situation (top layer). Based on this information, the renderer of all building elements that belong to the new situation is turned off at the beginning of the simulation, which means that only the old situation is visible. Then, at the start of each activity that belongs to the old situation, the renderer of the building elements that this activity is linked to is turned off so these elements disappear during this task. For the activities that are linked to the new situation, the renderer of its building elements is turned on at the end of the activity, so they appear in the screen as soon as this task is completed. This way, a 4D simulation of the Oude Kraan is created, and the reason why the old situation is also incorporated in this simulation is that road users had to use the existing infrastructure as a temporary route during the project (see Section 5.3.2), so these roads had to be present in the model as well.

Section 4.2 already explained that the estimated durations of construction activities are subject to changes, and to incorporate this phenomenon into the simulation model, a script called "Planning Deviation" is created and added to the "Databases" game object. The manual input for this script is the percentages of how much the duration of a certain activity can at most decrease or increase, and the script randomly changes the duration of each activity between these limits. Although this approach might not adequately represent the dynamic nature of a construction project because not every construction activity has the same sensitivity for schedule changes, it does make the simulation model more unpredictable which reflects the reality more than fixed activity durations.

5.5 TRAFFIC SIMULATION

Duration the reconstruction of the Oude Kraan, temporary routes have to be found for cars, cyclists, and pedestrians. Section 5.3.2 explained these temporary routes for each activity from the project planning in Table 5, and Table 6 shows that five different routes have to be modelled: on the old roadway when it is used by cars and cyclists, on the old roadway when it is only accessible for cyclists, on the new roadway, on the old promenade, and on the new bicycle highway. Each route is created by manually inserting waypoints. A waypoint consists of an empty GameObject and adding the "Waypoints" script (Figure 18) to these waypoints visualises them in the Unity scene. In Figure 19 it can be seen what a waypoint route in Unity looks like. To ensure a random, stochastic distance between entities, entities on the same route all start at a randomly selected waypoint. By implementing a lot of waypoints and minimising the number of entities on a route, the chances that multiple entities start at the same waypoint are minimised. The "Waypoints" script contains two additional options: if the "Can Loop" function is turned on, the traffic on that route returns to the first waypoint as soon as they reach the end of the round and follows the route again, and the "Is Moving Forward" function determines the direction of the traffic on the route. The "Can Loop" function is turned on in almost all cases because the traffic should not be allowed to stop once it reaches a certain point.

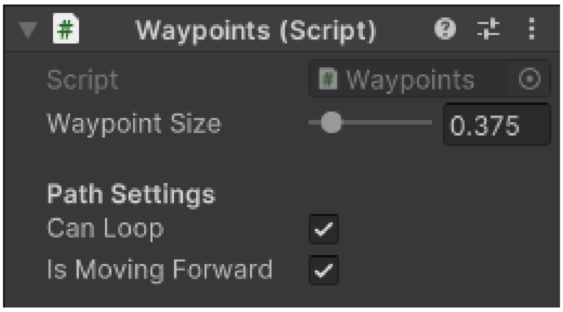

Waypoints (Script)
Script: Waypoints
Waypoint Size: 0.375
Path Settings
Can Loop ☑
Is Moving Forward ☑

Figure 18: The "Waypoints" script in the Unity Inspector

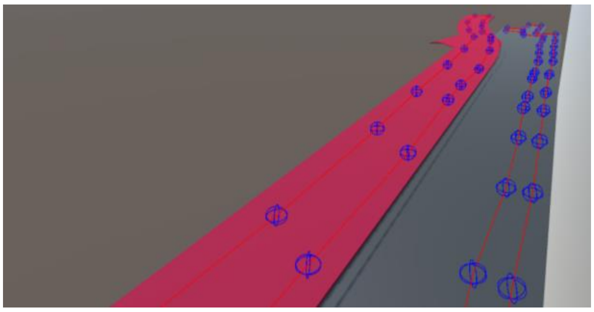
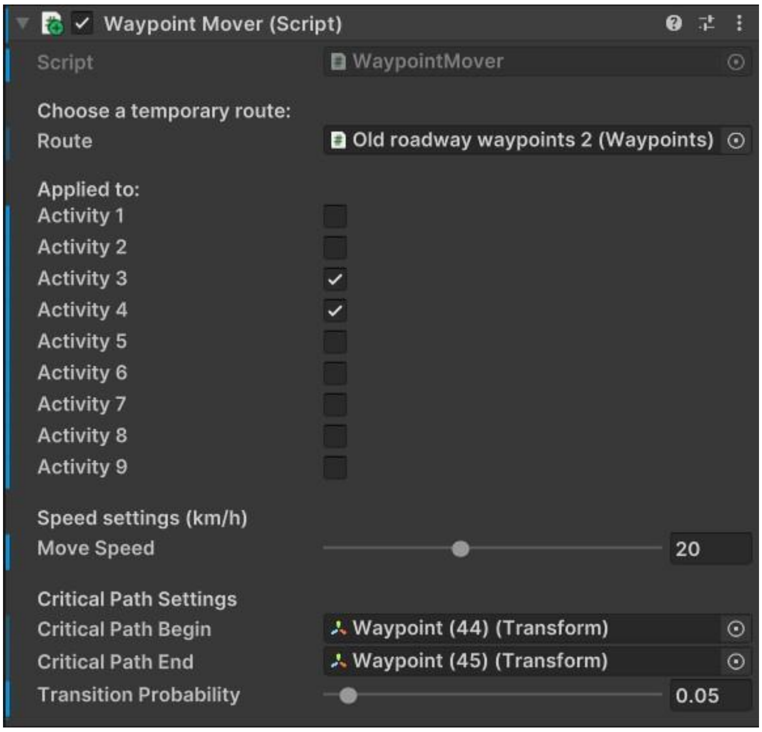


Figure 19: Visualisation of two waypoint routes in Unity

The script that executes the traffic simulation is called "Waypoint Mover", and the Unity Inspector in Figure 20 shows how the traffic is modelled in Unity. The Inspector displays detailed information about the currently selected GameObject, which is the bicycle from situation 2 in this case. The first manual input for the traffic simulation is to enter the route which is used by the selected road user, which is the route on the old roadway for cyclists in situation 2 in this case. Next, since each route exists only temporarily, it should be indicated for a road user during which activities the selected route is used, which is activity 3-5 in situation 2 (Table 6). The move speed of a road user also needs to be entered in the Inspector. For the move speed of cars, the CROW guidelines (CROW, 2020a) mandate that this speed is at most 30 km/h because cars share the road with cyclists in this model. Since a road is not wide enough for entities to overtake each other, entities who share a certain road follow the same route in the model and have therefore also the same speed. Therefore, the speed of cars should be equal to the speed of cyclists which is assumed to be 20 km/h. However, for some reason, the move speed of road users in the model increased if the number of entities on a route increased. To fix this, the script divides the entered move speed by the number of entities on the route in order to keep the entered move speed. Finally, according to the interview results in Section 3.2.2, access intrusion is one of the main causes of struck-by danger. To incorporate access intrusion in the model, the Inspector offers the possibility to enter one location where road users can deviate from the route, and the chance that the road users intrude the workspace. The value for the Transition Probability in Figure 20 shows that in this case, the chance is 5% that the cyclist uses that pathway.



☑ Waypoint Mover (Script)

Script: WaypointMover

Choose a temporary route:

Route: Old roadway waypoints 2 (Waypoints)

Applied to:

Activity 1 ☐
Activity 2 ☐
Activity 3 ☑
Activity 4 ☑
Activity 5 ☐
Activity 6 ☐
Activity 7 ☐
Activity 8 ☐
Activity 9 ☐

Speed settings (km/h)

Move Speed: 20

Critical Path Settings

Critical Path Begin: Waypoint (44) (Transform)
Critical Path End: Waypoint (45) (Transform)
Transition Probability: 0.05

Figure 20: The Unity Inspector for the bicycle in situation 2

Before the spatial conflict with a road user can be detected, the space that is required for a road user has to be defined by a bounding box. For the size of these bounding boxes, several factors play a role. The length of the space in front of a road user equals its stopping distance, which can be calculated by Equation 5, where *V* is the speed of the road user:

[5] $$Stopping\ Distance = \frac{\left(\frac{V}{10}\right)^2}{2}$$

The length of the space behind the road user does not depend on any specific factor but is chosen rather arbitrarily. For the width of the space around road users, the traffic spaces from Table 8 are used. Since each road in this case study is used in two directions, the width of the space that is used by a single road user should equal half of the traffic space. Figure 21 shows the interface in the Unity Inspector that sets the dimensions of required traffic space for a car (where the length in front is automatically generated based on the move speed, and the other dimensions are entered manually). Figure 22 visualises for each road user in this case study how much space they require.

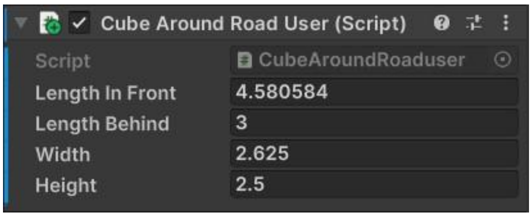

Cube Around Road User (Script)
Script CubeAroundRoaduser
Length In Front 4.580584
Length Behind 3
Width 2.625
Height 2.5

Figure 21: The interface to set the traffic space

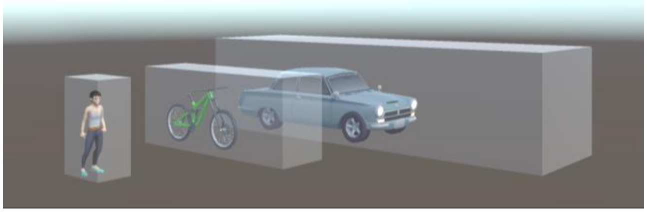


Figure 22: The road users and their required spaces

5.6 WORKSPACE GENERATION

5.6.1 Static workspaces

Not all workspaces that were identified in Section 2.2.1 will be modelled in this research because it would be too complicated to start from scratch and build a model that includes every single workspace. Therefore, we chose to focus on the most important ones based on the information that was provided in the semi-structured interviews, and these are the storage space, labour space, equipment space and hazard space. Other often mentioned spaces, such as the material path and the personnel path will not be included in this research due to the limited available time. Table 7 shows for each construction activity which workspaces are relevant, and what the dimensions of these spaces are. These dimensions are determined in cooperation with the project leader of the Blauwe Golven, and Table 7 only contains the width of each workspace because the length and height of each workspace stay the same. The length of each workspace is 80 metres because Dutch laws mandate that emergency services should be able to approach every location up to 40 metres (Overheid.nl, n.d.), which is still possible if a workspace is 80 metres long. For the height of a workspace, the arbitrary value of 4 metres is chosen because equipment such as trucks and excavators often have a maximum height of 4 metres.

Activity nr.:	Equipment space:	Hazard space:	Labour space:	Storage space:
1	Road width + 2x 1 m			
2	4 m x 4 m	1 m	4 m	4 m
3		1 m	4 m	4 m
4			Road width + 2x 1 m	3 m
5	Road width + 2x 1 m			
6			Width of greenery	
7				
8	Road width + 2x 1 m			
9	Road width + 2x 1 m			3 m

Table 7: Workspaces resulting from each activity

In addition to these workspaces that are required for the actual work, there are also some spaces legally required to be present. Table 8 shows the relevant information that is subtracted from the CROW guidelines (CROW, 2020a), and Figure 23 is added to visualise the meaning of the mentioned spaces. The traffic space already includes the avoidance space (see Figure 23), so the total hazard space is equal to the sum of the free space and the demarcation space. Table 8 shows that the total hazard space is 0.75 metres if the road adjacent to the construction activities is used by cars and/or cyclists, and 0.65 metres if the adjacent road is used by pedestrians only.

Road user:	Traffic space:	Free space:	Demarcation space:	Avoidance space:
Cars	5.25 m	0.60 m	0.50 m	0.25 m
Cyclists	2.50 m	0.60 m	0.50 m	0.25 m
Pedestrians	1.50 m	N/A	0.50 m	0.15 m

Table 8: Relevant CROW guidelines

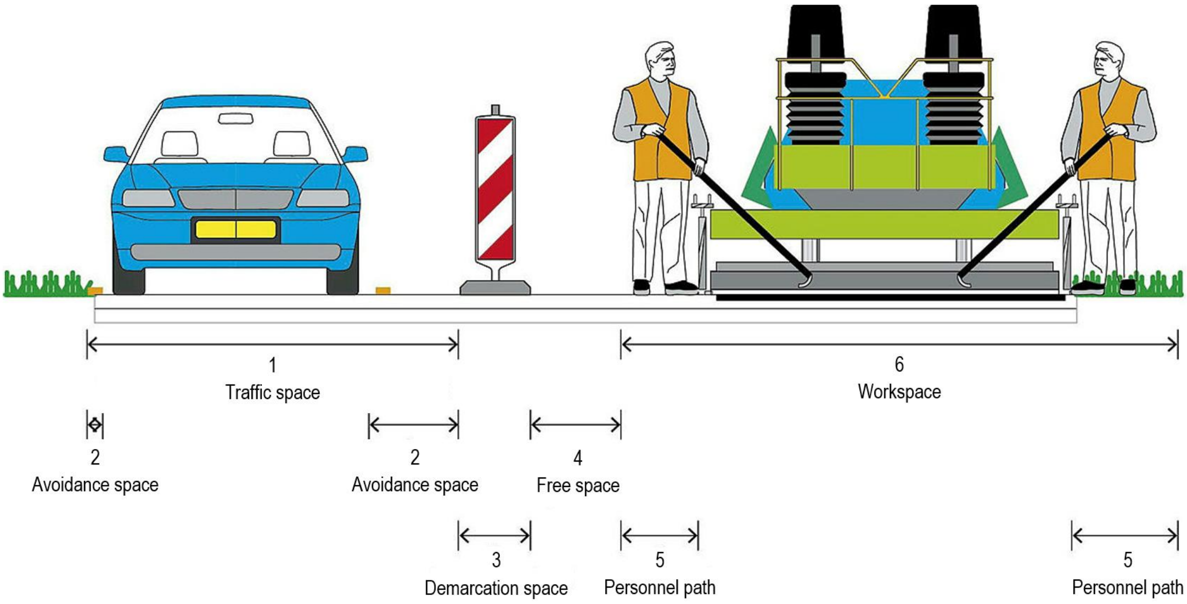
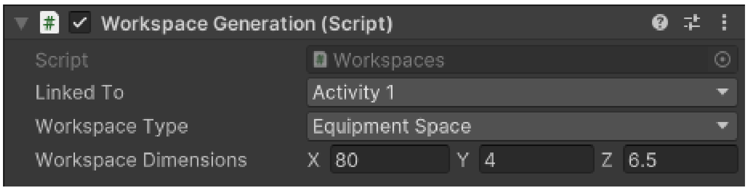


Figure 23: Cross-section of a road construction project (CROW, 2020a)

The “Workspace Generation” script can be attached to each workspace, and with the two dropdown menus the activity to which the workspace belongs and the workspace type can be selected (Figure 24). The selected activity ensures that the workspace (dis)appears at the right moment in the simulation, and the workspace type determines the colour of the workspace because the four workspace types have different colours in the simulation. Finally, the information from Table 7 and Table 8 could be entered in the workspace dimension fields.


Workspace Generation (Script)

Script: Workspaces
Linked To: Activity 1
Workspace Type: Equipment Space
Workspace Dimensions: X 80 Y 4 Z 6.5

Figure 24: The Unity Inspector for the equipment space of activity 1

5.6.2 Dynamic workspaces

Next to these static workspaces, this project also contains some dynamic workspaces that will be modelled (see Section 2.2.1 for more information on static and dynamic workspaces). During activities 3 and 4, cars were not allowed on the roadway and cyclists used a small part on one side of the roadway. The remainder of the roadway was used during these activities: to remove that part of the pavement and remove the sewage system (activity 3) and to pave the new roadway with bricks (activity 4). Figure 25 illustrates the situation during situation 3: on the left, the part of the old roadway that was used by cyclists is visible. During these activities, an excavator sometimes used this part to execute certain tasks. Therefore, a dynamic workspace representing this excavator should be included in the model. To show how the situation in Figure 25 is modelled in Unity, Figure 35 in Appendix II contains a screenshot of this activity in Unity. Both figures contain the same elements: the roadway on the left, the hazard space, the labour space for removing the sewage system, another hazard space, and a space for storing the soil that comes out of the trench.


Figure 25: The actual situation during the execution of activity 3 (image taken by ing. J.H. Withaar)

Next to that, the dynamic workspaces for the asphalt paving in activity 7 will be modelled, which includes a truck, a paver, and a roller. In the simulation model developed by Dalence et al. (2021), relevant information such as the road dimensions (length and width) and roller characteristics (quantity, width, speed, and number of required passes) can be entered. Based on this information, the model creates an Excel file with the coordinates of the roller(s) at each moment in time. In this case study, activity 7 includes the asphalt paving of the bicycle highway. The width of the bicycle highway is 4.5 metres, and for the length of the road, the length of a work zone is taken, which is 80 metres. Only one roller is used, which is 2 metres wide. The resulting file with the roller coordinates is placed in the "Resources" folder in Unity.

Unity does not have a built-in CSV reader, so the developed script has to split the string data from the file. The script should be attached to an empty GameObject in the Unity scene, together with the "Waypoints" script that visualises the waypoints (which is also done for the waypoints in Section 5.5). Then, a waypoint is instantiated as a child of the empty GameObject for each pair of coordinates and is positioned at these coordinates. However, the waypoints should also have the right direction and location. To achieve that, it is possible to enter the four coordinates in the Unity Inspector that indicate the boundaries. These four points define a rectangular area within which the path will be transformed and fitted, and the path from the CSV file will be scaled and translated to fit within this rectangle. In order to do so, the following method was created. First, the script finds the axis-aligned bounding box (AABB) of the original path (for more information on AABBs, see Section 2.3.3). Then, this AABB is transformed to fit within the AABB of the rectangle that is defined by the entered coordinates, and this same transformation is applied to each point of the path. This approach only works for equipment that follows a straight path, because a curved path cannot be transformed according to this approach.

For the paving equipment, the "Can Loop" function is turned off, which means that the equipment starts at the end of the path and does not return to the first waypoint and follows the path again, which is what the traffic in the simulation does (Section 5.5). Moreover, the paving equipment always starts at the first waypoint of its route, opposite to the traffic which starts at a random waypoint. Figure 36 in Appendix II shows how this situation looks like in Unity.

5.7 SITE SAFETY ASSESSMENT

5.7.1 Results

Table 9 shows for each combination of road user and workspace type what the corresponding SI is. To get this matrix, each type of road user is given a score that expresses its relative danger compared to each other, and each workspace type is also given a score that represents its relative vulnerability compared to each other. For example, cars are considered to be the most dangerous group of road users so they receive the highest score, and the labour space is seen as the most vulnerable workspace since that is the place where construction workers move around. Multiplying the scores for each combination results in the SI values.

	Car (0.5)	Cyclist (0.33)	Pedestrian (0.17)
Equipment Space (0.3)	0.15	0.10	0.05
Hazard Space (0.1)	0.05	0.03	0.02
Labour Space (0.5)	0.25	0.17	0.08
Storage Space (0.1)	0.05	0.03	0.02

Table 9: Severity Indexes (SI) for each combination of road user and workspace

Next, to implement the SAT algorithm (Section 2.3.3) in Unity, an existing Unity project was retrieved from GitHub (Fennell, 2017). Two scripts are used from this project: the "Cube" script which is adopted without any alterations and attached to each workspace that is checked for possible collision, and a script where the actual calculations from the SAT are executed which is adopted and tailored to the model.

After applying the SAT algorithm with the SI values from Table 9 to the developed simulation model, the dilemma was that a stochastic model needs to be run enough times to understand its predictions without running it so many times as to waste resources. In this case, it was chosen to run the model ten times and based on the collected data, the risk quantification method that is explained in Section 4.5 is executed. This results in the graph in Figure 26 where the SSI is plotted for each construction activity, so it shows for each activity of the construction schedule if the site layout results in an increased risk of struck-by accidents. To interpret the risk in the resulting graph correctly, Table 10, which is adapted from the matrices used by Collado-Mariscal et al. (2022) and Cortés-Pérez et al. (2020), shows which actions should be taken according to the SSI value. The reasoning behind the chosen SSI values is based on the values for collisions with the labour space: the risk starts to be moderate once a pedestrian can enter the labour space, significant once a cyclist can enter the labour space, and intolerable once a car can enter the labour space. Based on Figure 26, Table 10, and the activity durations in Table 5, we can conclude that 62% of the total project duration the risk is trivial or tolerable, meaning that there is no action required. A moderate risk where appropriate actions have to be taken occurs 23% of the time, 8% of the time the risk is significant which suggests that it would be wise to wait until the risk has been lowered before starting the work, and another 8% of the time there is intolerable risk, so performing the work before the risk is mitigated is not allowed then.

Risk:	Description:	SSI:
Trivial	No specific action is required	0.00 – 0.02
Tolerable	There is no need to improve the preventive action	0.02 – 0.08
Moderate	It is necessary identify appropriate actions to reduce the risk	0.08 – 0.17
Significant	Work should not commence until the risk has been reduced	0.17 – 0.25
Intolerable	You must not carry out the work until the risk is reduced	0.25 – ∞

Table 10: Actions to be taken according to the SSI

Moreover, a heatmap is created that shows how dangerous a certain spot is, i.e. how often a collision occurs at that exact location based on the registered coordinates of all workspace collisions in ten simulation runs (Figure 27). This heatmap is created in Microsoft Excel, where two axes are created that show the whole range of the project coordinates, with intervals of 0.5 coordinates. Next, it is calculated how often a collision occurred in each possible coordinate combination during ten simulation runs. After applying the “Conditional Formatting” option in Excel, a heatmap is generated where the colour scale varies between red squares for the locations where a collision happened the most often, until green squares where no collision occurred. The map of the project location is added in the background to indicate the exact position of the dangerous locations.

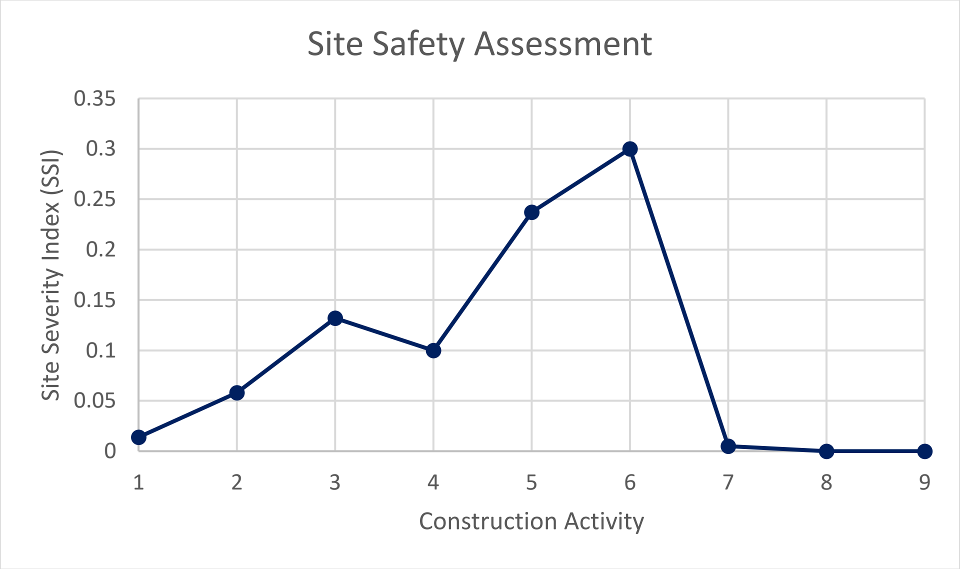


Figure 26: Quantification of the struck-by danger for each construction activity

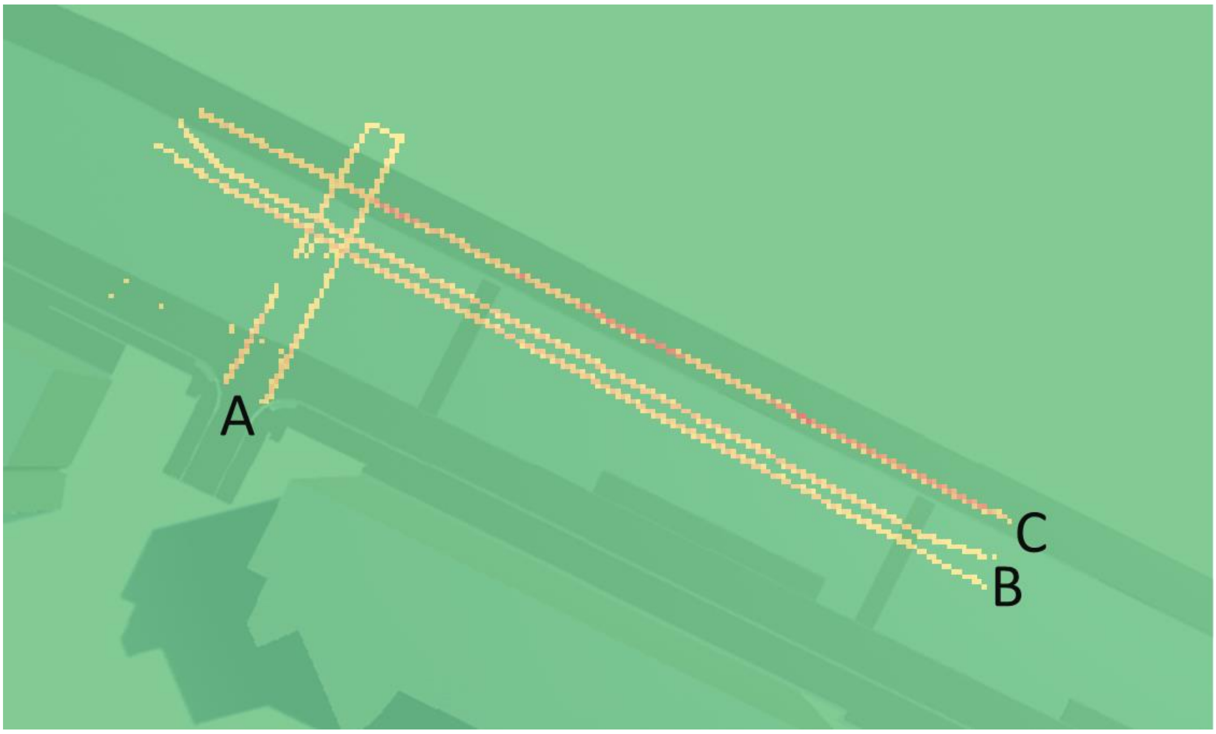


Figure 27: A heatmap with the most dangerous project locations

Based on the graph in Figure 26 and the map in Figure 27, several causes for struck-by danger could be indicated. The collision danger during activities 1 and 2 can be explained by access intrusion into the workspace (see Section 5.5 for an explanation of how this is modelled). The path of this intrusion is perpendicular to the work zone and indicated with the letter A in Figure 27, and Figure 37 in Appendix II shows how this looks like in Unity. Next, the risks during activities 3 and 4 are mostly due to the excavator who uses the same road as cyclists (this situation is explained in Section 5.6.2). The two paths (caused by cyclists travelling in two directions) are indicated with the letter B in Figure 27, and Figure 38 in Appendix II shows a collision between the excavator and a cyclist. The struck-by danger during activities 5 and 6 is indicated with the letter C in Figure 27 and this danger can be explained by the fact that the CROW guidelines are violated in this phase. The CROW guidelines dictate that the road should be 5.25 metres if it is used in two directions. However, the road adjacent to the construction activities which is used by cars and cyclists is only 5 metres wide, and the demarcation was placed upon the road which leaves only 4.5 metres for traffic. Thus, if the whole width of the road could be used by traffic, it would still be smaller than the required 5.25 metres. The explanation from the superintendent of this project is that after completion of the project, cyclists will use the bicycle street and this road is only used by cars, and if a road is only used by cars the required width is smaller than when it is used by cyclists as well. However, this means that during construction, the space that is needed for the cars and cyclists on this road collides with the hazard space and sometimes even the labour space of the activities during these days (which is called buffer intrusion according to Section 1.3). Most collisions can be attributed to this cause, because Figure 27 shows that these spots are often red-coloured, indicating a high occurrence of collisions. This lack of space is visualised in Figure 39 in Appendix II.

5.7.2 Risk Mitigation

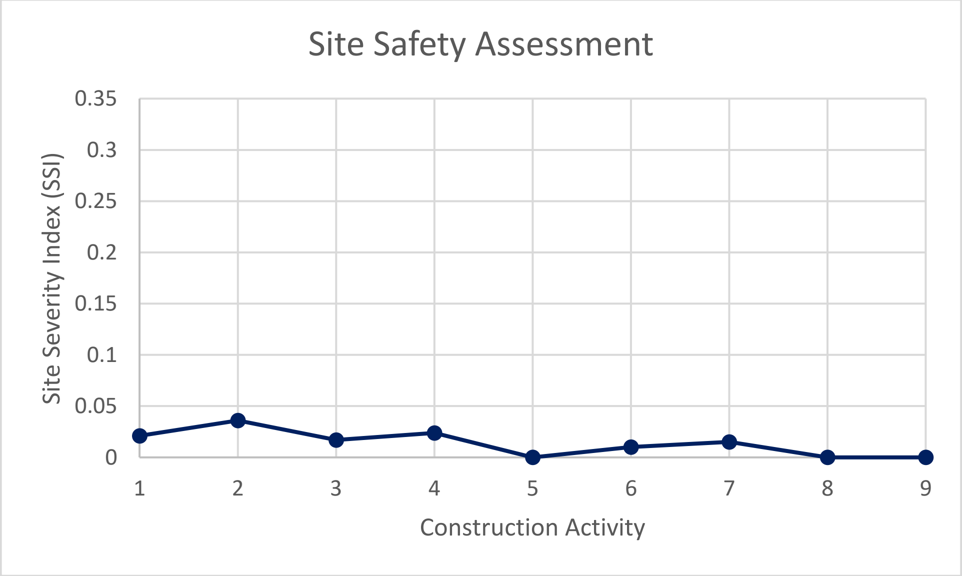


Figure 28: Quantification of the struck-by danger after implementing risk mitigation measures

The goal of this section is to come up with several measures that can decrease the struck-by danger by eliminating all moderate, significant, and intolerable risks that were detected in Section 5.7.1. These measures are the following:

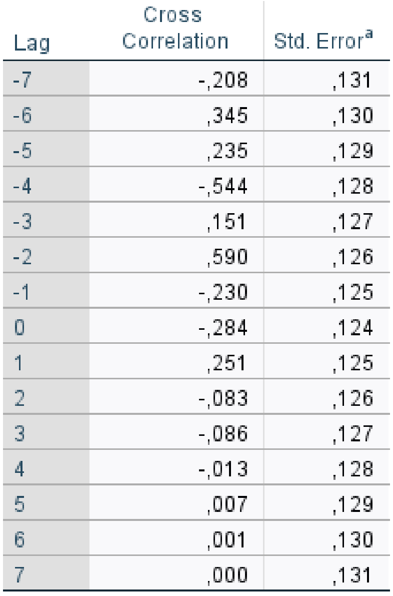
1. During activities 3 and 4, the excavator and the cyclists are not allowed to use the same road anymore. Therefore, cyclists should use the promenade, where they should walk next to their bicycles.
2. During activities 5 and 6, cars cannot use the road in two directions anymore. They should be regulated by traffic lights so that two cars cannot pass each other anymore next to the work zone.

After implementing these measures in the model, the simulation was run again ten times, and applying the risk quantification method to these results yields the graph in Figure 28. In this graph, the scale of the vertical axis was kept the same as the graph in Figure 26 to make the differences between both graphs visible at a glance. In this new situation, 46% of the time there is trivial risk, and the risk is tolerable for the remaining 54% of the time, which indicates that the suggested measures are sufficient to make this construction site a safe place to work.

5.8 MODEL VERIFICATION AND VALIDATION

5.8.1 Verification

In this section, the reliability of the developed simulation model is established. The term “reliability” refers to the consistency of a measurement or the repeatability of such measurements (Bruton et al., 2000). Section 5.7.1 mentioned that the simulation was run ten times to get the results, and the reliability of these runs is determined by analysing the extent to which each simulation run results in the same outcome. Cross-correlation is a method that analyzes how two sets of data, which change over time, are related to each other. It looks at whether changes in one set of data happen simultaneously with changes in the other, or if there's a delay between them (if they are lagged) (The Odum Institute, 2017). The data that was compared included for each moment of the simulation the total number of collisions at that moment. This statistical test was executed in SPSS and Figure 29 contains the comparison of simulation runs 1 and 2, which shows that a trend similar to the first run could be identified two days earlier in the second run with a correlation coefficient of 0.590. Table 11 shows the correlation coefficients of all comparisons (the lag values of each comparison are not recorded).



Lag	Cross Correlation	Std. Error^a
-7	-,208	,131
-6	,345	,130
-5	,235	,129
-4	-,544	,128
-3	,151	,127
-2	,590	,126
-1	-,230	,125
0	-,284	,124
1	,251	,125
2	-,083	,126
3	-,086	,127
4	-,013	,128
5	,007	,129
6	,001	,130
7	,000	,131

Figure 29: The SPSS output

	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9	Run 10
Run 1		0.590	0.522	0.514	0.766	0.433	0.360	0.714	0.614	0.738
Run 2			0.571	0.763	0.730	0.638	0.724	0.568	0.612	0.580
Run 3				0.544	0.430	0.544	0.451	0.527	0.520	0.355
Run 4					0.499	0.659	0.672	0.525	0.511	0.527
Run 5						0.630	0.529	0.724	0.762	0.565
Run 6							0.561	0.648	0.635	0.506
Run 7								0.453	0.564	0.534
Run 8									0.754	0.779
Run 9										0.707
Run 10										

Table 11: Correlation coefficients

After comparing the different time series that result from the simulation runs, we can conclude based on Table 12 that there is mostly a moderate correlation between the different simulation runs (the interpretations of the correlation strengths in Table 12 are adopted from Asuero et al. (2006)). This moderate strength of the correlation coefficients indicates that there is a relationship between the time series, and this consistency in the patterns across different runs suggests that the simulation is reliable in capturing important aspects of the system. This consistency could indicate that certain aspects of the model are robust and reproducible. Nevertheless, the correlation is not overly strong. This suggests that while the simulation runs are similar, they also have some variability or differences. The sources of this variability are the stochastic elements of the model, such as the percentage of pedestrians that intrude into the work zone or the number of road users that pass the work zone at a certain moment. Nevertheless, we can conclude that the similarity between the time series implies that the simulation model captures the essential dynamics of the system being studied. However, it's essential to validate whether these similarities align with real-world observations or theoretical expectations to ensure the model's accuracy and relevance, which is done in Section 5.8.2.

Size of r:	Interpretation:	Occurrence:
0.00 to 0.29	Little if any correlation	0.00%
0.30 to 0.49	Low correlation	13.33%
0.50 to 0.69	Moderate correlation	62.22%
0.70 to 0.89	High correlation	24.44%
0.90 to 1.00	Very high correlation	0.00%

Table 12: Strength of correlation

5.8.2 Validation

A simulation model is valid if it accurately represents the underlying phenomenon that it claims to measure (Harris et al., 2020). According to Harris et al. (2020), two types of validity should be considered in the design of a simulation: face validity and construct validity. Face validity is the subjective view users have of how realistic a simulation is, and the design of the simulation and its technical capabilities are important determinants of face validity (Harris et al., 2020). Face validation often consists of asking experts whether the simulation is reasonable, so if the logic and the relationship between the input and output of the model is correct (Sargent, 2010).

A disadvantage of face validity is that it depends highly on the superficial visual features of the simulation model, which means that a simulation can have face validity and still be useless (Harris et al., 2020). Therefore, construct validity measures more objectively the extent to which the simulation is an accurate representation of the real task. This involves testing hypotheses about how the model should behave based on established theories or empirical evidence. Construct validity requires empirical evidence based on real-world data to demonstrate that the simulation model effectively captures the essential elements of the real-world phenomena.

Since construct validity would require the input of actual data on struck-by accidents and near misses during the case project, evaluating the construct validity is not possible in this research because there is not sufficient data available on near misses (which was already indicated as a common problem in Section 1.3). Therefore, it is chosen to assess only the face validity, which is done by presenting the research of this master thesis to a team of experts from Roelofs and asking them to assess the developed tool based on the following criteria:

- Adoption: The extent to which the concept of a collision detection tool could be a valuable addition to the current design process (so this criterium is about the general concept of using a spatial-temporal analysis to predict and prevent struck-by danger, not about the tool that is developed in this thesis).
- Functionality: The extent to which the tool that is developed in Unity behaves as expected, i.e. if it contains all required functions and possibilities for achieving the intended aim.
- Usability: How easy it seems for the participant to learn to use and navigate the tool.
- Flexibility: The extent to which it is possible to apply this tool to different project types.

Six experts took part in the validation process and Table 12 shows the functions of the six respondents. The experts were asked to assess each criterion with a mark between 1 and 10 and to provide additional comments. The complete questionnaires that were answered by the team of experts can be found in Appendix III on page 70. Below, the answers of the experts can be found, and it is important to note that respondent 4 only rated each criterion with a mark between 1 and 10, but did not provide any additional comments. Furthermore, the criterion "Functionality" was only assessed by 5 of the 6 respondents.

Respondent:	Function:
1	Manager Innovation & Development
2	Commercial Manager
3	Designer
4	Designer
5	Regional Manager Road Construction
6	Project Manager

Table 13: Functions of the respondents to the survey

With regard to the adoption of this concept (Figure 30), all respondents are very enthusiastic. According to respondent 1, the visualisations give more insight into the dangerous situation than the current paper-based safety plans, respondent 2 says that this concept adds value to the construction process by determining the safety in different project phases, and thinks it is interesting that the effect of interventions can be visualised immediately. Furthermore, respondent 3 also thinks that this concept seems suitable to apply, for example by starting the conversation about struck-by danger in an early project phase and involving the client in these discussions about potential risks. The role of the client is also mentioned by respondent 5, who thinks that clients will realise sooner and quicker how struck-by danger can be prevented, provided that this concept is given a prominent place in the design process. Respondent 6 also sees perspective for the concept, but only when the resulting tool is kept simple and practical to use.

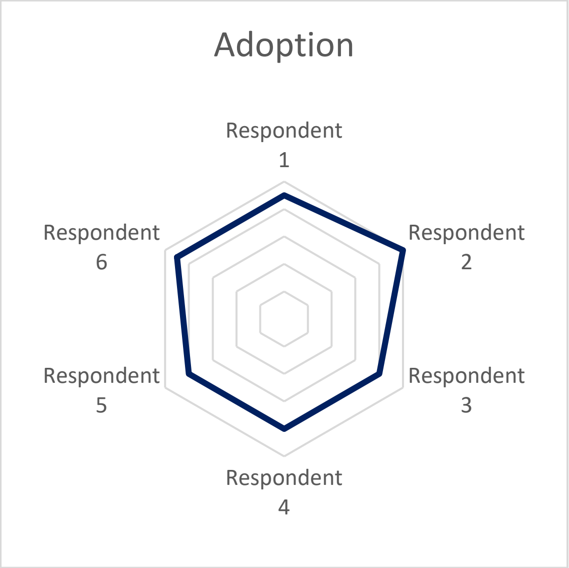


Figure 30: The perceived adoption of the collision detection concept

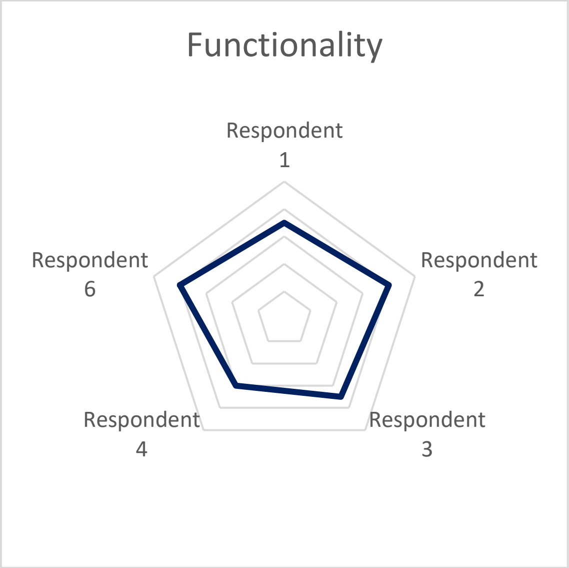


Figure 31: The perceived functionality of the developed tool

When asked about the functionality of the designed tool itself (Figure 31), most respondents agree with each other that it is so far, so good, but that the tool needs to be developed further before it can be used in practice. Respondents 1 and 6 both say that the basic principle is good but that further expansion is desired in additional research. Respondent 2 is impressed by the current progress but wonders how the behaviour of traffic participants and road workers can be included in this tool because this is difficult to predict, and this concern is shared by respondent 3. Next to that, respondent 3 also thinks that the tool functions well but is curious to see how much work it is to change the locations of the temporary routes if they are altered in the design, and wonders if it would be possible that changes in the design software are immediately applied in Unity as well. Finally, respondent 5 thinks that the contractor's traffic in a work zone should also be included in the collision risk before the tool can be implemented in practice.

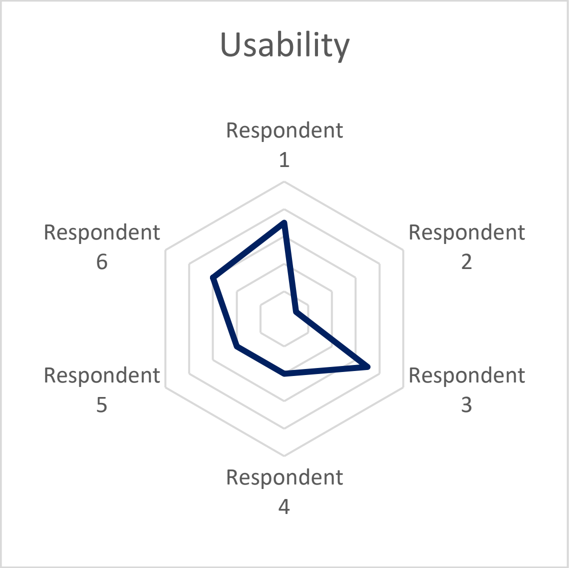


Figure 32: The perceived usability of the developed tool

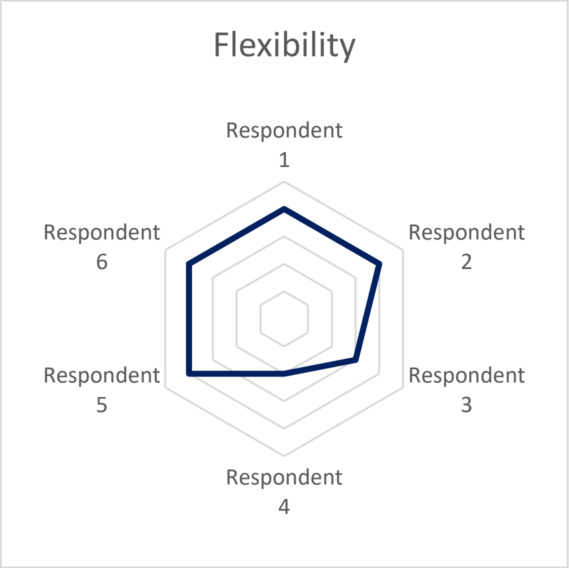


Figure 33: The perceived flexibility of the developed tool

The usability of this tool (Figure 32) receives the lowest marks in the survey. This can be explained by the functions within Roelofs of respondents 1, 2, 5 and 6, who all mention that they are not a designer and are not going to use the tool. Nevertheless, they expect that using the tool should not be a problem for (experienced) designers. Of the two designers that filled out the survey, respondent 3 says the usability can be improved because there are still a lot of manual actions required in the current tool. Finally, the criterium flexibility (Figure 33) indicates how easy it is to use the tool for many different projects, which is rated quite high by all respondents who do not see a problem for specific project types. Respondent 6 only comments that an elaborated library has to be created that contains the components for all possible project situations.

Interestingly, the respondents who are designers are more sceptical than respondents who have another function (average scores of 6.25 and 7.26, respectively). The only criterion where they score higher is the usability (5.5 and 4.5, respectively). Thus, designers rate the usability higher since they are more experienced in using similar (design) tools, and are more critical of the tool's performance because they are the ones who are supposed to use the tool in their daily work and are therefore more focused on whether the tool could be used right now. Other experts such as the innovation manager or project manager are more looking in the future, and see mainly the potential of the tool. In general, the experts who took part in the validation process are all quite enthusiastic about the developed tool, so it is safe to say that the developed tool is valid based on face validation.

6

DISCUSSION

In this chapter, the developed framework and the resulting tool will be discussed. With regard to the framework, the stochastic approach to modelling construction activity durations adds realism to the simulation. However, it relies heavily on assumptions about the variability of construction processes, and incorporating more historical project data could increase the accuracy of this variability. The same applies to the inclusion of stochastic elements like variable speeds and road user counts, which adds complexity to the simulation and hence reflects real-world traffic dynamics, but accurately modelling road user behaviour and interactions remains challenging. In the workspace generation and allocation phase, input from experts ensures that workspaces are appropriately sized and located, but this input is still based on subjective judgments. An example of how this can be improved is that the width of a trench for constructing or removing a sewer is fixed in this case study, but in reality the width of a trench depends on its depth. The NLA has guidelines for this ratio, and integrating these existing guidelines (or historical project data) increases the accuracy of generating and allocating workspaces. It would be even possible to make the trench width variable in the tool, so that it is easily visible what the impact of increasing the trench depth is on the available space.

The developed tool offers a detailed simulation of the project area, which allows a contractor to identify potential conflicts between road traffic and workspaces before they occur in reality. As a result, proactive measures can be taken to reduce risks before work begins, such as redesigning work zones or implementing additional traffic control measures. So, contractors can use the tool to evaluate the impact of different planning scenarios on struck-by danger and make adjustments accordingly. Using this tool in a case study did not unveil an enormous amount of spatial conflicts, because an existing project is used for this case study which means that the site layout, including the workspaces and traffic spaces, was already planned by a team of experts from Roelofs. Nevertheless, the case study did prove that this methodology can be applied in the site layout planning, so for a new project it can speed up the process of choosing temporary routes.

A difference between the simulation model of the Oude Kraan and the real-life project is that in the model, it was at a certain moment not possible for cars to pass each other without violating the CROW guidelines concerning hazard- and traffic spaces. However, in reality, cars did pass each other at that moment, so apparently, it was no problem to neglect these guidelines. This implies that the conflicts in the simulation model did not represent any accidents, but rather a violation of guidelines. Nevertheless, these guidelines do not exist without reason, so it would be advisable to maintain the required spaces.

The developed tool can function as a useful tool for designers, although it first needs to be developed further because the tool does not contain all situations that could be encountered in practice yet. To illustrate this, often the simplest situation was modelled in the case study, such as all storage spaces for bricks and soil were located as close to the work as possible. In reality, a contractor might opt for storing these resources in a depot if there is not enough space on the construction site, but this results in construction vehicles entering the traffic zone which are quite dangerous movements according to the interviews that were conducted in this research. Modelling these movements can be done with dynamic workspaces, and this study already showed how such dynamic workspaces could be included in the simulation model by simulating an asphalt paving activity and the movement of an excavator. Therefore, it would not be a major challenge to extend the range of dynamic workspaces for other purposes as well. With regard to dynamic workspaces, it also has to be noted that dynamism is especially important for unpredictable movements. The abovementioned dynamic workspaces (of the asphalt paver and excavator), could also have been a large static workspace since their movements were known beforehand. However, dynamic movements of walking pedestrians, for example, are unknown beforehand which is why an agent-based simulation of pedestrians would add more realistic dynamism to the tool, and hence increase the safety awareness of construction designers.

Furthermore, it can be argued that the dependence of the spaces around road users on the speed of the road user had no added value in the approach since only the width of its required space influenced struck-by danger. However, if this concept is developed further and used for other applications as well, these variable spaces can play a role in determining what the maximum traffic intensity on a road with a certain speed limit could be, for example.

It is also important to note that the used SI values for each conflict type are from the point of view of the construction worker, but it would also be possible to look at the danger for road users. In that case, pedestrians would receive the highest score of all road users because they are the most vulnerable group of road users, and the equipment space would receive the highest score of all workspace types because the area where equipment moves around is the most dangerous for road users. However, Section 1.2 already explained that accidents from the point of view of road users are called struck-against accidents, but that the focal point of this research is placed on struck-by accidents where the force of contact is provided by the traffic.

Implementing the tool is in line with Roelofs' vision to integrate the design and execution of construction projects, so it aids designers in checking if their design is feasible. Nevertheless, performing detailed simulations, analysing the results of the simulations, and taking appropriate actions to ensure safety may require additional time and resources from construction designers. Not all construction designers are familiar with using advanced simulation tools such as Unity. This may require additional training to ensure that the full potential of the tool is realised which also leads to an increased workload. Furthermore, the implementation of such advanced simulation tools might involve initial investments for licenses and training, which could be a barrier for smaller contractors or projects with limited resources. Despite these extra efforts and costs, the eventual return on investment is a much more efficient way to plan temporary routes and storage locations and to analyse if the legally required hazard spaces and traffic spaces are being maintained, so it is worth the extra effort.

7

CONCLUSION

7.1 SUMMARY AND FINDINGS

The research presented in this thesis has four major contributions to the academic literature, which are: (1) exploring struck-by accidents and near misses in road construction projects by combining the existing literature on causes for struck-by dangers with the experience of construction workers that is captured through semi-structured interviews, (2) introducing a novel approach that analyses spatial-temporal conflicts between road users and workspaces associated with construction activities, and (3) proofing this concept by implementing the proposed method into a serious game engine that dynamically detects and quantifies the struck-by danger of road construction projects during the entire execution phase.

The results of the case study of the Oude Kraan showed that 62% of the total project duration the risk is trivial or tolerable, moderate for 23% of the time, significant for 8% of the time, and another 8% of the time the risk is intolerable. The causes for struck-by danger that were present in the case study are access intrusion, buffer intrusion and working outside the work zone. The first occurred because pedestrians and cyclists were modelled to leave the predefined path and find a shorter route with a certain probability, and the latter two occurred because the project did not contain sufficient space to stick to all CROW guidelines about mandatory hazard- and traffic spaces. Possible interventions that can be suggested for the project from the case study are that cyclists should use the promenade where they should walk next to their bicycles, to ensure that the excavator and the cyclists do not use the same road anymore during activities 3 and 4. The second recommendation is to regulate the cars that want to access the Blauwe Golven by traffic lights so that they cannot use the road in two directions next to the work zone anymore. If these measures are implemented, the risk is reduced to only trivial or tolerable risk, although safety is not an exact science with a firm boundary between safe and unsafe. It rather predicts the most dangerous location, which can then be eliminated after which another location is the most dangerous one. So in a sense, there are always some significant and intolerable risks that should receive attention, until all risks from a construction site are eliminated.

According to the simulation model, the only struck-by danger that then occurs is caused by access intrusion of pedestrians. This danger is mentioned by all participants of the interviews, and these interviews also showed that this is the most unpredictable kind of danger because one of the interviewees mentioned that pedestrians do not listen to the directions on the signs but often choose the shortest route possible by intruding into the workspace. Since the nature of this problem lies more in the behaviour of road users than in appropriate traffic control measures, the best way to eliminate the remaining risk would be to either start a campaign that makes road users aware of the danger they can cause or to close the work zone completely and prevent that any road user can get near the project. With the latter measure, the project can be executed quicker and hence cheaper as well. So, the most ideal measure to prevent struck-by danger is to close a project location entirely for road traffic, but this is often not allowed by the governmental institution that is the client of the project. Hopefully, the methodology that is developed in this research can give governmental institutions the insight to realise that it is sometimes better to close a road entirely.

7.2 FURTHER RESEARCH

To test and develop the simulation model further, additional research is required. This research can for example focus on modelling other construction activities and associated workspace types that are relevant based on the semi-structured interviews, but not incorporated in this research. Secondly, the model validation can be extended by applying this methodology in an earlier stage because the case study in this research was a post hoc analysis of an existing project where the temporary routes were already planned and the resulting dangers identified. However, it might also be interesting to use this methodology at the start of a project, to predict unforeseen circumstances on an ad hoc basis. This results in a more robust model validation if the predicted results are compared with the real-life outcomes after the project is finished. Finally, other research can focus on developing an interactive user interface for the developed simulation model, which makes it easier for practitioners to apply this methodology to their projects.

8

BIBLIOGRAPHY

AbouRizk, S., Halpin, D., Mohamed, Y., & Hermann, U. (2011). Research in Modeling and Simulation for Improving Construction Engineering Operations. *Journal of Construction Engineering and Management*, *137*(10), 843–852. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000288

Abualdenien, J., & Borrmann, A. (2022). Levels of detail, development, definition, and information need: a critical literature review. *Journal of Information Technology in Construction*, *27*, 363–392. https://doi.org/10.36680/j.itcon.2022.018

Adeoye-Olatunde, O. A., & Olenik, N. L. (2021). Research and scholarly methods: Semi-structured interviews. *JACCP: Journal of the American College of Clinical Pharmacy*, *4*(10), 1358–1367. https://doi.org/10.1002/jac5.1441

Agdas, D., & Ellis, R. D. (2010). IT in transportation construction: opportunities and barriers to implementation. *Proceedings of the International Conference on Computing in Civil and Building Engineering*, 223–228.

Ajibade, T. (2020). *BIM integration for construction health and safety* [Master thesis, Metropolia UAS and HTW Berlin]. http://www.theseus.fi/handle/10024/339344

Akinci, B., Fischer, M., Kunz, J., & Levitt, R. (2002). Representing Work Spaces Generically in Construction Method Models. *Journal of Construction Engineering and Management*, *128*(4), 296–305. https://doi.org/10.1061/(ASCE)0733-9364(2002)128:4(296)

Akinci, B., Fischer, M., Levitt, R., & Carlson, R. (2000). Formalization and Automation of Time-Space Conflict Analysis. *Journal of Computing in Civil Engineering*, *16*(2), 124–134. https://doi.org/10.1061/(ASCE)0887-3801(2002)16:2(124)

Al Ameri, A., & Nasaruddin, N. A. N. (2020). Client Related Changes Affecting Construction Schedule Performance. *International Journal of Sustainable Construction Engineering and Technology*, *11*(3). https://doi.org/10.30880/ijscet.2020.11.03.006

Algemeen Dagblad. (2014, October 24). *Wegwerkers lamgeslagen na dood collega bij ongeluk A12*. https://www.ad.nl/binnenland/wegwerkers-lamgeslagen-na-dood-collega-bij-ongeluk-a12~acfb9566/

Archive of Destruction. (n.d.). *De Blauwe Golven*. Retrieved October 26, 2023, from https://archiveofdestruction.com/artwork/de-blauwe-golven/#:~:text=De%20Blauwe%20Golven%20(Blue%20Waves,between%20art%20and%20urban%20design.

Asuero, A. G., Sayago, A., & González, A. G. (2006). The Correlation Coefficient: An Overview. *Critical Reviews in Analytical Chemistry*, *36*(1), 41–59. https://doi.org/10.1080/10408340500526766

Autodesk. (n.d.). *-HATCH (Command)*. Retrieved December 1, 2023, from https://help.autodesk.com/view/ACADWEB/ENU/?guid=AutoCAD_Web_Help_List_Commands_Hatch_html

Baradan, S., & Usmen, M. A. (2006). Comparative Injury and Fatality Risk Analysis of Building Trades. *Journal of Construction Engineering and Management*, *132*(5), 533–539. https://doi.org/https://doi.org/10.1061/(ASCE)0733-9364(2006)132:5(533)

Behm, M. (2005). Linking construction fatalities to the design for construction safety concept. *Safety Science*, *43*(8), 589–611. https://doi.org/10.1016/j.ssci.2005.04.002

BIM Onderwijs. (n.d.). *LOD: Level Of Detail of Level Of Development*. Retrieved March 5, 2024, from https://www.bimonderwijs.nl/kennisbank/wat-is-bim/lod-level-of-detail-level-of-development/

Borrmann, A., & Rank, E. (2009). Specification and implementation of directional operators in a 3D spatial query language for building information models. *Advanced Engineering Informatics*, *23*(1), 32–44. https://doi.org/10.1016/j.aei.2008.06.005

Bourlon, S., & Boton, C. (2019). *Automating the Integration of 4D Models in Game Engines for a Virtual Reality-Based Construction Simulation* (pp. 123–132). https://doi.org/10.1007/978-3-030-30949-7_14

Brown, S., Harris, W., Brooks, R. D., & Dong, X. S. (2021). *Fatal and Nonfatal Struck-by Injuries in the Construction Industry, 2011-2019*. https://stacks.cdc.gov/view/cdc/115582

Bruton, A., Conway, J. H., & Holgate, S. T. (2000). Reliability: What is it, and how is it measured? *Physiotherapy*, *86*(2), 94–99. https://doi.org/10.1016/S0031-9406(05)61211-4

Bryden, J. E., & Andrew, L. B. (1999). Serious and Fatal Injuries to Workers on Highway Construction Projects. *Transportation Research Record: Journal of the Transportation Research Board*, *1657*(1), 42–47. https://doi.org/10.3141/1657-06

Bryden, J. E., Andrew, L. B., & Fortuniewicz, J. S. (1998). Work Zone Traffic Accidents Involving Traffic Control Devices, Safety Features, and Construction Operations. *Transportation Research Record: Journal of the Transportation Research Board*, *1650*(1), 71–81. https://doi.org/10.3141/1650-09

Bryden, J. E., Andrew, L. B., & Fortuniewicz, J. S. (2000). Intrusion Accidents on Highway Construction Projects. *Transportation Research Record: Journal of the Transportation Research Board*, *1715*(1), 30–35. https://doi.org/10.3141/1715-05

BZK. (n.d.). *Basisregistratie Grootschalige Topografie*. Retrieved November 2, 2023, from https://www.geobasisregistraties.nl/basisregistraties/grootschalige-topografie/basisregistratie-grootschalige-topografie

Charef, R., Alaka, H., & Emmitt, S. (2018). Beyond the third dimension of BIM: A systematic review of literature and assessment of professional views. *Journal of Building Engineering*, *19*, 242–257. https://doi.org/10.1016/j.jobe.2018.04.028

Chavada, R., Dawood, N., & Kassem, M. (2014). Construction workspace management: the development and application of a novel nD planning approach and tool. *Electronic Journal of Information Technology in Construction*, *17*, 213–236. http://www.itcon.org/2012/13

Choi, B., Lee, H.-S., Park, M., Cho, Y. K., & Kim, H. (2014). Framework for Work-Space Planning Using Four-Dimensional BIM in Construction Projects. *Journal of Construction Engineering and Management*, *140*(9). https://doi.org/10.1061/(ASCE)CO.1943-7862.0000885

Chong, H. Y., Lopez, R., Wang, J., Wang, X., & Zhao, Z. (2016). Comparative Analysis on the Adoption and Use of BIM in Road Infrastructure Projects. *Journal of Management in Engineering*, *32*(6). https://doi.org/10.1061/(ASCE)ME.1943-5479.0000460

Collado-Mariscal, D., Cortés-Pérez, J. P., Cortés-Pérez, A., & Cuevas-Murillo, A. (2022). Proposal for the Integration of Health and Safety into the Design of Road Projects with BIM. *Buildings*, *12*(10), 1753. https://doi.org/10.3390/buildings12101753

Cortés-Pérez, J. P., Cortés-Pérez, A., & Prieto-Muriel, P. (2020). BIM-integrated management of occupational hazards in building construction and maintenance. *Automation in Construction*, *113*, 103115. https://doi.org/10.1016/j.autcon.2020.103115

Costin, A., Adibfar, A., Hu, H., & Chen, S. S. (2018). Building Information Modeling (BIM) for transportation infrastructure – Literature review, applications, challenges, and recommendations. *Automation in Construction*, *94*, 257–281. https://doi.org/10.1016/j.autcon.2018.07.001

CROW. (2011). *Afstemmen en hinderanalyse bij werk in uitvoering*. CROW.

CROW. (2020a). *Standaardmaatregelen op niet-autosnelwegen – Werk in Uitvoering 96b - 2020*. CROW.

CROW. (2020b). *Werken op niet-autosnelwegen – Werk in Uitvoering 96b - 2020*. CROW.

Dalence, A. R. R., Vahdatikhaki, F., & Dorée, A. (2021). *Integrating VR and Simulation to deal with complex planning challenges: A case of asphalt compaction* [University of Twente]. https://purl.utwente.nl/essays/85820

Dawood, N., & Mallasi, Z. (2006). Construction Workspace Planning: Assignment and Analysis Utilizing 4D Visualization Technologies. *Computer-Aided Civil and Infrastructure Engineering*, *21*(7), 498–513. https://doi.org/10.1111/j.1467-8667.2006.00454.x

Debnath, A. K., Blackman, R., & Haworth, N. (2015). Common hazards and their mitigating measures in work zones: A qualitative study of worker perceptions. *Safety Science*, *72*, 293–301. https://doi.org/10.1016/j.ssci.2014.09.022

Doan, D. T., Ghaffarianhoseini, A., Naismith, N., Zhang, T., Rehman, A. U., Tookey, J., & Ghaffarianhoseini, A. (2019). What is BIM? A Need for A Unique BIM Definition. *MATEC Web of Conferences*, *266*. https://doi.org/10.1051/matecconf/201926605005

Dubois, A., & Gadde, L.-E. (2002). The construction industry as a loosely coupled system: implications for productivity and innovation. *Construction Management and Economics*, *20*(7), 621–631. https://doi.org/10.1080/01446190210163543

Eastman, C., Lee, J., Jeong, Y., & Lee, J. (2009). Automatic rule-based checking of building designs. *Automation in Construction*, *18*(8), 1011–1033. https://doi.org/10.1016/j.autcon.2009.07.002

Eischet, O. (2023, January 23). *BIM Maturity Levels Explained*. https://medium.com/specter-automation-insights/bim-maturity-levels-explained-922060c163ef

ElNimr, A., & Mohamed, Y. (2011). Loosely coupled visualization of industrial construction simulation using a gaming engine. *Proceedings of the 2011 Winter Simulation Conference (WSC)*, 3577–3587. https://doi.org/10.1109/WSC.2011.6148052

Elsheikh, A. (2022). *Construction workspace management using 4D BIM*. 040010. https://doi.org/10.1063/5.0099410

Ershadi, M., Jefferies, M., Davis, P., & Mojtahedi, M. (2022). Implementation of Building Information Modelling in infrastructure construction projects: a study of dimensions and strategies. *International Journal of Information Systems and Project Management*, *9*(4), 43–59. https://doi.org/10.12821/ijispm090403

Fennell, M. (2017). *3D Separating Axis Theorem implementation in Unity*. GitHub. https://github.com/irixapps/Unity-Separating-Axis-SAT

Flores, M., Al-Ashaab, A., Mörth, O., Usó, P. C., Pinar, H., Alfaraj, F., & Yu, M. (2018). *The Construction Value Chain in a BIM Environment* (pp. 255–262). https://doi.org/10.1007/978-3-319-99707-0_32

Francisco, K. N. B., Concepcion, J. D., Mojica, A. R., & Montes, S. A. B. (2019). Philippines First: An Edutainment 3D Game for Android Mobile Platform using Separating Axis Theorem (SAT) Algorithm. *Innovatus*, *2*(1), 12–15.

Gambatese, J. A., & Hallowell, M. (2011). Enabling and measuring innovation in the construction industry. *Construction Management and Economics*, *29*(6), 553–567. https://doi.org/10.1080/01446193.2011.570357

Gan, W., & Ge, Y. (2023). Application Strategy of BIM Technology in Municipal Road Design. *Journal of World Architecture*, *7*(3), 15–20. https://doi.org/10.26689/jwa.v7i3.4768

Google Earth Pro. (2021). *Blauwe Golven Arnhem*. [Online]. http://www.google.com/earth/index.html

Guevremont, M., & Hammad, A. (2019). Defining Levels of Development for 4D Simulation of Major Capital Construction Projects. In *Advances in Informatics and Computing in Civil and Construction Engineering* (pp. 77–83). Springer International Publishing. https://doi.org/10.1007/978-3-030-00220-6_10

Guevremont, M., & Hammad, A. (2020). Levels of development definition for 4D simulation of construction projects. *International Journal on Hydropower and Dams*, *27*(4), 76–92. https://doi.org/10.1007/978-3-030-00220-6_10

Guo, H., Yu, Y., & Skitmore, M. (2017). Visualization technology-based construction safety management: A review. *Automation in Construction*, *73*, 135–144. https://doi.org/10.1016/j.autcon.2016.10.004

Guo, S.-J. (2002). Identification and Resolution of Work Space Conflicts in Building Construction. *Journal of Construction Engineering and Management*, *128*(4), 287–295. https://doi.org/10.1061/(ASCE)0733-9364(2002)128:4(287)

Gürcanli, G. E., & Müngen, U. (2013). Analysis of Construction Accidents in Turkey and Responsible Parties. *Industrial Health*, *51*(6), 581–595. https://doi.org/10.2486/indhealth.2012-0139

Hadikusumo, B. H. W., & Rowlinson, S. (2004). Capturing Safety Knowledge Using Design-for-Safety-Process Tool. *Journal of Construction Engineering and Management*, *130*(2), 281–289. https://doi.org/10.1061/(ASCE)0733-9364(2004)130:2(281)

Hall, J. W., & Lorenz, V. M. (1989). Characteristics of Construction-Zone Accidents. *Transportation Research Record*, *1230*, 20–27. https://onlinepubs.trb.org/Onlinepubs/trr/1989/1230/1230-003.pdf

Hammad, A., Setayeshgar, S., Zhang, C., & Asen, Y. (2012). Automatic generation of Dynamic Virtual Fences as part of BIM-based prevention program for construction safety. *Proceedings Title: Proceedings of the 2012 Winter Simulation Conference (WSC)*, 1–10. https://doi.org/10.1109/WSC.2012.6465164

Harris, D. J., Bird, J. M., Smart, P. A., Wilson, M. R., & Vine, S. J. (2020). A Framework for the Testing and Validation of Simulated Environments in Experimentation and Training. *Frontiers in Psychology*, *11*. https://doi.org/10.3389/fpsyg.2020.00605

Hegazy, T., & Elbeltagi, E. (1999). EvoSite: Evolution-Based Model for Site Layout Planning. *Journal of Computing in Civil Engineering*, *13*(3), 198–206. https://doi.org/10.1061/(ASCE)0887-3801(1999)13:3(198)

Heidary, M. S., Mousavi, M., Alvanchi, A., Barati, K., & Karimi, H. (2021, November 2). *Semi-automatic Construction Hazard Identification Method Using 4D BIM*. https://doi.org/10.22260/ISARC2021/0080

Hinze, J., & Godfrey, R. J. (2003). An evaluation of safety performance measures for construction projects. *Journal of Construction Research*, *04*(01), 5–15. https://doi.org/10.1142/S160994510300025X

Hinze, J., Huang, X., & Terry, L. (2005). The Nature of Struck-by Accidents. *Journal of Construction Engineering and Management*, *131*(2), 262–268. https://doi.org/10.1061/(ASCE)0733-9364(2005)131:2(262)

Hinze, J., Pedersen, C., & Fredley, J. (1998). Identifying Root Causes of Construction Injuries. *Journal of Construction Engineering and Management*, *124*(1), 67–71. https://doi.org/10.1061/(ASCE)0733-9364(1998)124:1(67)

Hire, S., Sandbhor, S., Ruikar, K., & Amarnath, C. B. (2021). BIM usage benefits and challenges for site safety application in Indian construction sector. *Asian Journal of Civil Engineering*, *22*(7), 1249–1267. https://doi.org/10.1007/s42107-021-00379-8

Igwe, C., Nasiri, F., & Hammad, A. (2022). Construction workspace management: critical review and roadmap. *International Journal of Construction Management*, *22*(10), 1960–1973. https://doi.org/10.1080/15623599.2020.1756028

Jannadi, O. A., & Almishari, S. (2003). Risk Assessment in Construction. *Journal of Construction Engineering and Management*, *129*(5), 492–500. https://doi.org/10.1061/(ASCE)0733-9364(2003)129:5(492)

Jin, Z., Gambatese, J., Liu, D., & Dharmapalan, V. (2019). Using 4D BIM to assess construction risks during the design phase. *Engineering, Construction and Architectural Management*, *26*(11), 2637–2654. https://doi.org/10.1108/ECAM-09-2018-0379

Johansen, K. W., Schultz, C., & Teizer, J. (2022). BIM-based Fall Hazard Ontology and Benchmark Model for Comparison of Automated Prevention through Design Approaches in Construction Safety. *Proceedings of the 29th EG-ICE International Workshop on Intelligent Computing in Engineering*, 408–417. https://doi.org/10.7146/aul.455.c231

Kamardeen, I. (2010). 8D BIM modelling tool for accident prevention through design. *Proceedings of the 26th Annual ARCOM Conference*, 281–289.

Karakhan, A., Rajendran, S., & Gambatese, J. (2018). Validation of Time-Safety Influence Curve Using Empirical Safety and Injury Data—Poisson Regression. *Construction Research Congress 2018*, 389–399. https://doi.org/10.1061/9780784481288.038

Koutamanis, A. (2020). Dimensionality in BIM: Why BIM cannot have more than four dimensions? *Automation in Construction*, *114*. https://doi.org/10.1016/j.autcon.2020.103153

Krijnen, T., & Van Berlo, L. A. H. M. (2016). Methodologies for requirement checking on building models: A technology overview. *13th International Conference on Design and Decision Support Systems in Architecture and Urban Planning*, 1–11.

Kuiper, J., Giesbertz, P., & Bloemhoff, A. (2007). *Aanrijdgevaar wegwerkers, deelrapport 4, vragenlijstonderzoek*. https://publications.tno.nl/publication/34616328/jYjbM1/kuiper-2007-aanrijdgevaar.pdf

Larsen, G. D., & Whyte, J. (2013). Safe construction through design: perspectives from the site team. *Construction Management and Economics*, *31*(6), 675–690. https://doi.org/10.1080/01446193.2013.798424

Latiffi, A. A., Brahim, J., Mohd, S., & Fathi, M. S. (2015). Building Information Modeling (BIM): Exploring Level of Development (LOD) in Construction Projects. *Applied Mechanics and Materials*, *773–774*, 933–937. https://doi.org/10.4028/www.scientific.net/AMM.773-774.933

Lee, Y.-C., Eastman, C. M., & Lee, J.-K. (2015). Validations for ensuring the interoperability of data exchange of a building information model. *Automation in Construction*, *58*, 176–195. https://doi.org/10.1016/j.autcon.2015.07.010

Lingard, H., Pirzadeh, P., Harley, J., Blismas, N., & Wakefield, R. (2014). *Safety in Design*. https://www.academia.edu/32970718/Safety_in_Design

Liu, B., Cai, T., Xiao, S., Fu, H., & Chu, W. (2019). Research on application of BIM technology in municipal road construction. *IOP Conference Series: Earth and Environmental Science*, *330*(2). https://doi.org/10.1088/1755-1315/330/2/022078

Malekitabar, H., Ardeshir, A., Sebt, M. H., & Stouffs, R. (2016). Construction safety risk drivers: A BIM approach. *Safety Science*, *82*, 445–455. https://doi.org/10.1016/j.ssci.2015.11.002

Mallasi, Z. (2004). Identification and Visualisation of Construction Activities' Workspace Conflicts Utilising 4D CAD/VR Tools. *1st ASCAAD International Conference*, 235–253.

Mallasi, Z. (2006). Dynamic quantification and analysis of the construction workspace congestion utilising 4D visualisation. *Automation in Construction*, *15*(5), 640–655. https://doi.org/10.1016/j.autcon.2005.08.005

Marx, A., & Köning, M. (2013). Modeling and simulating spatial requirements of construction activities. *2013 Winter Simulation Conference*, 3294–3305. https://doi.org/https://doi.org/10.1109/WSC.2013.6721694

McGrath, C., Palmgren, P. J., & Liljedahl, M. (2019). Twelve tips for conducting qualitative research interviews. *Medical Teacher*, *41*(9), 1002–1006. https://doi.org/10.1080/0142159X.2018.1497149

Messi, L. (2022). *Development of a BIM-based simulator for workspace management in construction*. https://iris.univpm.it/handle/11566/295537

Messi, L., García de Soto, B., Carbonari, A., & Naticchia, B. (2022a). Intelligent BIM-based spatial conflict simulators: A comparison with commercial 4D tools. *Proceedings of the 39th International Symposium on Automation and Robotics in Construction (ISARC 2022)*, 550–557. https://doi.org/https://doi.org/10.22260/ISARC2022/0078

Messi, L., García de Soto, B., Carbonari, A., & Naticchia, B. (2022b). Spatial conflict simulator using game engine technology and Bayesian networks for workspace management. *Automation in Construction*, *144*. https://doi.org/10.1016/j.autcon.2022.104596

Mezrag, Y., & Boton, C. (2021). *Integrating 4D Simulations and Virtual Reality Environments: An Innovative Prototype* (pp. 103–114). https://doi.org/10.1007/978-3-030-88207-5_11

Migilinskas, D., Popov, V., Juocevicius, V., & Ustinovichius, L. (2013). The Benefits, Obstacles and Problems of Practical Bim Implementation. *Procedia Engineering*, *57*, 767–774. https://doi.org/10.1016/j.proeng.2013.04.097

Mileff, P. (2023). Collision Detection in 2D Games. *Production Systems and Information Engineering*, *11*(3), 10–26. https://doi.org/10.32968/psaie.2023.3.2

Mirzaei, A., Nasirzadeh, F., Parchami Jalal, M., & Zamani, Y. (2018). 4D-BIM Dynamic Time–Space Conflict Detection and Quantification System for Building Construction Projects. *Journal of Construction Engineering and Management*, *144*(7). https://doi.org/10.1061/(ASCE)CO.1943-7862.0001504

MnDOT. (2015). *Work Zone Crash Report*. https://www.dot.state.mn.us/trafficeng/workzone/swzsc/workzonecrashes.pdf

Monarch Innovation. (2023, November 30). *Different Level of Development (LOD) in BIM 100, 200, 300, 350, 400, 500*. https://www.monarch-innovation.com/bim-level-of-development-lod-300-350-400-500

Moroney, W. F., & Moroney, B. W. (1991). Utilizing a Microcomputer Based Flight Simulation in Teaching Human Factors in Aviation. *Proceedings of the Human Factors Society Annual Meeting*, *35*(7), 523–527. https://doi.org/10.1518/107118191786754806

Nevada LTAP. (n.d.). *Basic Work Zone Traffic Control*. Retrieved September 13, 2023, from https://nvltap.com/training-3/workzone-safety/

Newcastle University. (2017). *Physics Tutorial 4: Collision Detection*. https://research.ncl.ac.uk/game/mastersdegree/gametechnologies/previousinformation/physics4collisiondetection/

Ning, X., Qi, J., & Wu, C. (2018). A quantitative safety risk assessment model for construction site layout planning. *Safety Science*, *104*, 246–259. https://doi.org/10.1016/j.ssci.2018.01.016

NLA. (n.d.). *Basis Inspectiemodule: Aanrijdgevaar bij werkzaamheden op en langs de openbare weg*. https://www.arbowetweter.nl/system/files/bim_aanrijdgevaar-bij-werkzaamheden-op-en-langs-de-openbare-weg_2015_tcm335-369292.pdf

NLA. (2022). *Monitor arbeidsongevallen 2021*. https://www.nlarbeidsinspectie.nl/publicaties/rapporten/2022/09/05/monitor-arbeidsongevallen-2021

Nnaji, C., Gambatese, J., & Lee, H. W. (2018). Work Zone Intrusion: Technology to Reduce Injuries & Fatalities. *Professional Safety*, *63*(4), 36–41.

OpenStreetMap. (n.d.). *Welkom bij OpenStreetMap!* Retrieved January 25, 2024, from https://www.openstreetmap.org/

OSHA. (2011). *Construction Focus Four: Struck-By Hazards*. https://www.osha.gov/sites/default/files/struckby_ig.pdf

Osorio-Sandoval, C. A., Tizani, W., Pereira, E., Ninić, J., & Koch, C. (2022). Framework for BIM-Based Simulation of Construction Operations Implemented in a Game Engine. *Buildings*, *12*(8), 1199. https://doi.org/10.3390/buildings12081199

Overheid.nl. (n.d.). *Beleidsregels Bereikbaarheid en Bluswatervoorziening*. Retrieved January 18, 2024, from https://lokaleregelgeving.overheid.nl/CVDR643598/1

Price, L. C., Chen, J., & Cho, Y. K. (2021). Dynamic Crane Workspace Update for Collision Avoidance During Blind Lift Operations. *Proceedings of the 18th International Conference on Computing in Civil and Building Engineering*, 959–970. https://doi.org/10.1007/978-3-030-51295-8_66

Riley, D. R., & Sanvido, V. E. (1995). Patterns of Construction-Space Use in Multistory Buildings. *Journal of Construction Engineering and Management*, *121*(4), 464–473. https://doi.org/10.1061/(ASCE)0733-9364(1995)121:4(464)

Roelofsgroep. (n.d.-a). *Over ons*. Retrieved October 3, 2023, from https://www.roelofsgroep.nl/over-ons/

Roelofsgroep. (n.d.-b). *Plankaart Blauwe Golven*. Retrieved November 18, 2023, from https://www.roelofsgroep.nl/projecten/blauwe-golven/

Roelofsgroep. (n.d.-c). *Reconstuctie Blauwe Golven, Oude Kraan en Roermondsplein Arnhem*. Retrieved October 26, 2023, from https://www.roelofsgroep.nl/projecten/reconstuctie-blauwe-golven-oude-kraan-en-roermondsplein-arnhem/

Roelofsgroep. (2022, March 24). *Roelofs behaalt Veiligheidsladder trede 3*. https://www.roelofsgroep.nl/roelofs-behaalt-veiligheidsladder-trede-3/

Rubio, M. C., Menéndez, A., Rubio, J. C., & Martínez, G. (2005). Obligations and Responsibilities of Civil Engineers for the Prevention of Labor Risks: References to European Regulations. *Journal* *of Professional Issues in Engineering Education and Practice*, *131*(1), 70–75. https://doi.org/10.1061/(ASCE)1052-3928(2005)131:1(70)

Safety Culture Ladder. (n.d.). *Safety Culture Ladder Steps*. Retrieved June 21, 2023, from https://safetycultureladder.com/en/the-safety-culture-ladder/safety-culture-ladder-steps/

Sakhakarmi, S., & Park, J. (2022). Improved intrusion accident management using haptic signals in roadway work zone. *Journal of Safety Research*, *80*, 320–329. https://doi.org/10.1016/j.jsr.2021.12.015

Sampaio, A. Z., Constantino, G. B., & Almeida, N. M. (2022). 8D BIM Model in Urban Rehabilitation Projects: Enhanced Occupational Safety for Temporary Construction Works. *Applied Sciences*, *12*(20). https://doi.org/10.3390/app122010577

Sargent, R. G. (2010). Verification and validation of simulation models. *Proceedings of the 2010 Winter Simulation Conference*, 166–183. https://doi.org/10.1109/WSC.2010.5679166

Shafiq, M. T., & Afzal, M. (2021). Improving Construction Job Site Safety with Building Information Models: Opportunities and Barriers. *37th CIB W78 Information Technology for Construction Conference*, 1014–1036. https://doi.org/10.1007/978-3-030-51295-8_71

Shang, Z., & Shen, Z. (2016). A Framework for a Site Safety Assessment Model Using Statistical 4D BIM-Based Spatial-Temporal Collision Detection. *Construction Research Congress 2016*, 2187–2196. https://doi.org/10.1061/9780784479827.218

Shehab, T., & Phu, L. (2015). *Accident Patterns in Road Construction Work Zones*. *39*(2), 46–57.

Shen, X., & Marks, E. (2016). Near-Miss Information Visualization Tool in BIM for Construction Safety. *Journal of Construction Engineering and Management*, *142*(4). https://doi.org/10.1061/(ASCE)CO.1943-7862.0001100

Siebelink, S., Voordijk, H., Endedijk, M., & Adriaanse, A. (2021). Understanding barriers to BIM implementation: Their impact across organizational levels in relation to BIM maturity. *Frontiers of Engineering Management*, *8*(2), 236–257. https://doi.org/10.1007/s42524-019-0088-2

Szymberski, R. (1997). Construction Project Safety Planning. *TAPPI Journal*, *80*(11), 69–74.

Teizer, J., & Cheng, T. (2015). Proximity hazard indicator for workers-on-foot near miss interactions with construction equipment and geo-referenced hazard areas. *Automation in Construction*, *60*, 58–73. https://doi.org/10.1016/j.autcon.2015.09.003

Thabet, W. Y., & Beliveau, Y. J. (1994). Modeling Work Space to Schedule Repetitive Floors in Multistory Buildings. *Journal of Construction Engineering and Management*, *120*(1), 96–116. https://doi.org/10.1061/(ASCE)0733-9364(1994)120:1(96)

The Odum Institute. (2017). *Time Series Cross-Correlations and the USDA Feed Grains Database (1876–2015): U.S. Barley and Oats Prices per Bushel*. SAGE Publications, Ltd. https://doi.org/10.4135/9781473995765

The Washington Post. (2023, March 22). *6 road construction workers die in Maryland when car crashes into them*. https://www.washingtonpost.com/dc-md-va/2023/03/22/maryland-workers-killed-crash-work-zone-beltway/

Trani, M. L., Cassano, M., Todaro, D., & Bossi, B. (2015). BIM Level of Detail for Construction Site Design. *Procedia Engineering*, *123*, 581–589. https://doi.org/10.1016/j.proeng.2015.10.111

Ullman, G. L., Finley, M. D., & Theiss, L. (2011). Categorization of Work Zone Intrusion Crashes. *Transportation Research Record: Journal of the Transportation Research Board*, *2258*(1), 57–63. https://doi.org/10.3141/2258-07

Unity. (n.d.). *Unity Student Plan*. Retrieved October 17, 2023, from https://unity.com/products/unity-student

Uusitalo, P., Seppänen, O., Lappalainen, E., Peltokorpi, A., & Olivieri, H. (2019). Applying Level of Detail in a BIM-Based Project: An Overall Process for Lean Design Management. *Buildings*, *9*(5), 109. https://doi.org/10.3390/buildings9050109

Vahdatikhaki, F., & Hammad, A. (2015). Dynamic equipment workspace generation for improving earthwork safety using real-time location system. *Advanced Engineering Informatics*, *29*(3), 459–471. https://doi.org/10.1016/j.aei.2015.03.002

Van Berlo, L. A. H. M., & Bomhof, F. (2014). Creating the Dutch National BIM Levels of Development. *Computing in Civil and Building Engineering*, 129–136. https://doi.org/10.1061/9780784413616.017

Van den Berg, M., Hartmann, T., & De Graaf, R. (2017). Supporting design reviews with pre-meeting virtual reality environments. *ITcon*, *22*, 305–321. https://www.itcon.org/paper/2017/16

Veenenbos en Bosch landschapsarchitecten. (2020). *Blauwe Golven*. https://veenenbosenbosch.nl/portfolio_page/keulse-poort-venlo/

Venema, A., Van Eijk, V., Kuiper, J., Drupsteen, L., Bloemhoff, A., Brinkhuis, B., & Jansen, W. (2008). De veiligheid van wegwerkers: ernst, omvang en oorzaken van aanrijdingen bij wegwerkzaamheden. *Tijdschrift Voor Toegepaste Arbowetenschap*, *21*(21), 74–82.

Venugopal, M., Eastman, C. M., Sacks, R., & Teizer, J. (2012). Semantics of model views for information exchanges using the industry foundation class schema. *Advanced Engineering Informatics*, *26*(2), 411–428. https://doi.org/10.1016/j.aei.2012.01.005

Vignali, V., Acerra, E. M., Lantieri, C., Di Vincenzo, F., Piacentini, G., & Pancaldi, S. (2021). Building information Modelling (BIM) application for an existing road infrastructure. *Automation in Construction*, *128*. https://doi.org/10.1016/j.autcon.2021.103752

VVN. (2023, October 16). *Wegwerkers luiden de noodklok; de werksituaties zijn te gevaarlijk*. https://vvn.nl/nieuws/wegwerkers-luiden-de-noodklok-de-werksituaties-zijn-te-gevaarlijk

Wang, Q., Guo, Z., Mintah, K., Li, Q., Mei, T., & Li, P. (2019). Cell-Based Transport Path Obstruction Detection Approach for 4D BIM Construction Planning. *Journal of Construction Engineering and Management*, *145*(3). https://doi.org/10.1061/(ASCE)CO.1943-7862.0001583

Weißmann, M., Edler, D., Keil, J., & Dickmann, F. (2023). Creating an Interactive Urban Traffic System for the Simulation of Different Traffic Scenarios. *Applied Sciences*, *13*(10). https://doi.org/10.3390/app13106020

Wildenauer, A. A. (2020). Critical Assessment of the Existing Definitions of BIM Dimensions on the Example of Switzerland. *International Journal of Civil Engineering and Technology*, *11*(4), 134–151. https://doi.org/10.34218/IJCIET.11.4.2020.012

Wong, J. M., Arico, M. C., & Ravani, B. (2011). Factors Influencing Injury Severity to Highway Workers in Work Zone Intrusion Accidents. *Traffic Injury Prevention*, *12*(1), 31–38. https://doi.org/10.1080/15389588.2010.525569

World Economic Forum. (2018). *An Action Plan to Accelerate Building Information Modeling (BIM) Adoption*. https://www3.weforum.org/docs/WEF_Accelerating_BIM_Adoption_Action_Plan.pdf

Yang, B., & Laursen, T. A. (2007). A contact searching algorithm including bounding volume trees applied to finite sliding mortar formulations. *Computational Mechanics*, *41*(2), 189–205. https://doi.org/10.1007/s00466-006-0116-z

Yin, R. K. (2018). *Case Study Research and Applications: Design and Methods* (Sixth edition). SAGE.

Zanen, P. P. A., Hartmann, T., Al-Jibouri, S. H. S., & Heijmans, H. W. N. (2013). Using 4D CAD to visualize the impacts of highway construction on the public. *Automation in Construction*, *32*, 136–144. https://doi.org/10.1016/j.autcon.2013.01.016

Zhang, S., Sulankivi, K., Kiviniemi, M., Romo, I., Eastman, C. M., & Teizer, J. (2015). BIM-based fall hazard identification and prevention in construction safety planning. *Safety Science*, *72*, 31–45. https://doi.org/10.1016/J.SSCI.2014.08.001

Zhang, S., Teizer, J., Lee, J.-K., Eastman, C. M., & Venugopal, M. (2013). Building Information Modeling (BIM) and Safety: Automatic Safety Checking of Construction Models and Schedules. *Automation in Construction*, *29*, 183–195. https://doi.org/10.1016/j.autcon.2012.05.006

Zhang, S., Teizer, J., Pradhananga, N., & Eastman, C. M. (2015). Workforce location tracking to model, visualize and analyze workspace requirements in building information models for construction safety planning. *Automation in Construction*, *60*, 74–86. https://doi.org/10.1016/j.autcon.2015.09.009

Zhao, D., Lucas, J., & Thabet, W. (2009). Using virtual environments to support electrical safety awareness in construction. *Proceedings of the 2009 Winter Simulation Conference (WSC)*, 2679–2690. https://doi.org/10.1109/WSC.2009.5429258

9

APPENDICES

9.1 APPENDIX I: INTERVIEW QUESTIONS

Project introduction

1. Could you please shortly introduce the project that we are talking about?
2. Which categories of road users were involved in this project? Think of cyclists, pedestrians, cars etc.
3. What do you consider as the most dangerous/vulnerable group of road users? Think of cyclists, pedestrians, cars etc.
4. Have you received complaints from road users about their perceived dangers during this project?
5. Have you experienced situations in this project where road users were a danger for construction workers?
6. Did a collision accident with a road user occur during the course of the project?
7. Have you experienced any near misses during the course of the project, i.e. situations in which a collision accident with a road user almost occurred?

Demarcations

8. Can you explain the detours/demarcations that were used in this project?
9. Did it occur that road users ignored the demarcation and entered the work zone?
10. Which of the following do you recognise from the project: full intrusion, buffer intrusion, moving workspace intrusion, access intrusion, debris intrusion?
11. Did it occur during this project that a part of a public roadway was used by a construction activity, e.g. by workers, equipment, or material storage?
12. Did it occur that construction workers had to leave the demarcated work zone in order to execute certain tasks?

Spaces

13. Was there enough space for each road users to pass the work zone safely?
14. To what extent did you maintain the CROW guidelines with regard to mandatory traffic spaces and hazard spaces?
15. Was there sufficient space within the work zone itself to execute activities, such as space for equipment to manoeuvre?
16. Did it occur during this project that there was not a suitable place for construction materials, which resulted in a storage place that could lead to safety hazards?
17. Were there any obstacles that obstructed the view on road traffic? (such as machines, piles of material, bends in the road, etc.)

Activities

18. Which specific activities of this project caused the most hindrance for road users?
19. To what extent did a too tight schedule lead to spatial conflicts?
20. To what extent did the supply of building materials cause struck-by danger? Did unloading activities happen on the public road?
21. Which choices during the design of the project resulted in dangerous situations with road users during the execution phase?
22. Have you other remarks about struck-by danger during this project, that are not mentioned yet?

General

23. What is in general the main cause of struck-by danger in your opinion?
24. Which construction activities are generally considered as dangerous for road users?
25. Do you wish that designers take struck-by danger more into account in the design phase? What do you expect from them, and what should they change compared to their current practices?

9.2 APPENDIX II: UNITY SCREENSHOTS

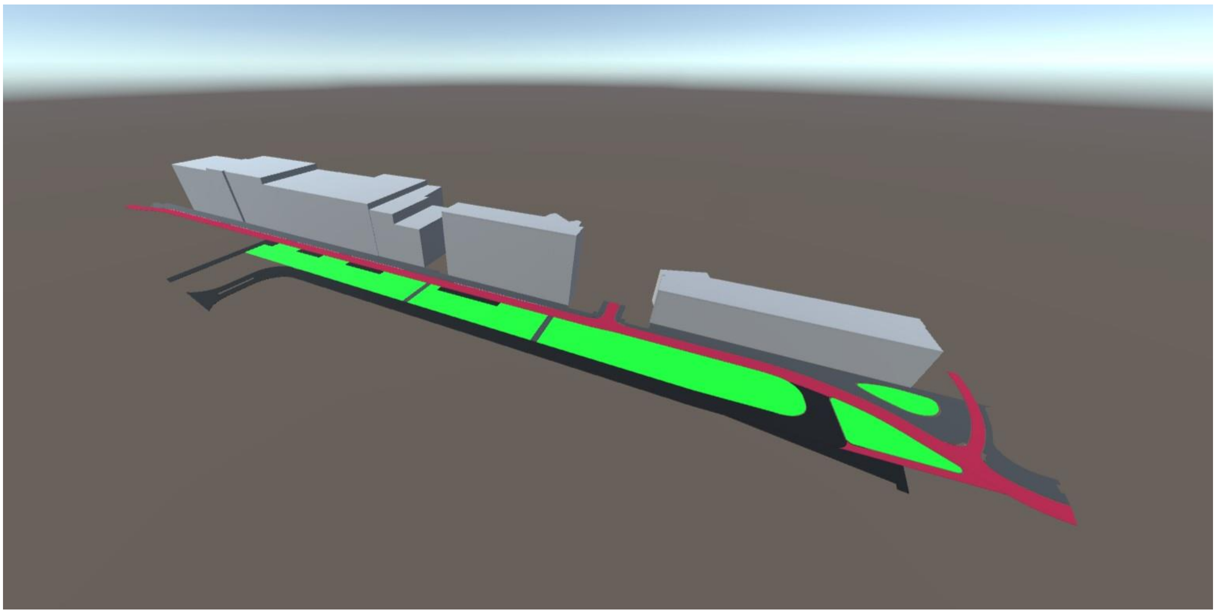


Figure 34: The 3D model of the Oude Kraan

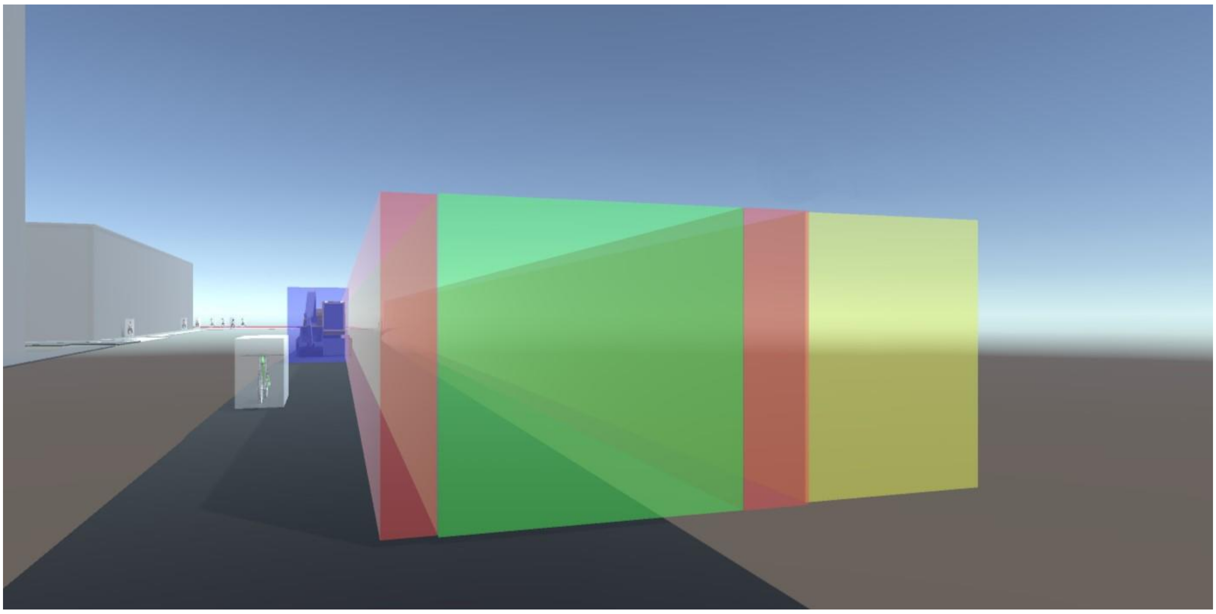


Figure 35: Removing the old sewage system underneath the roadway

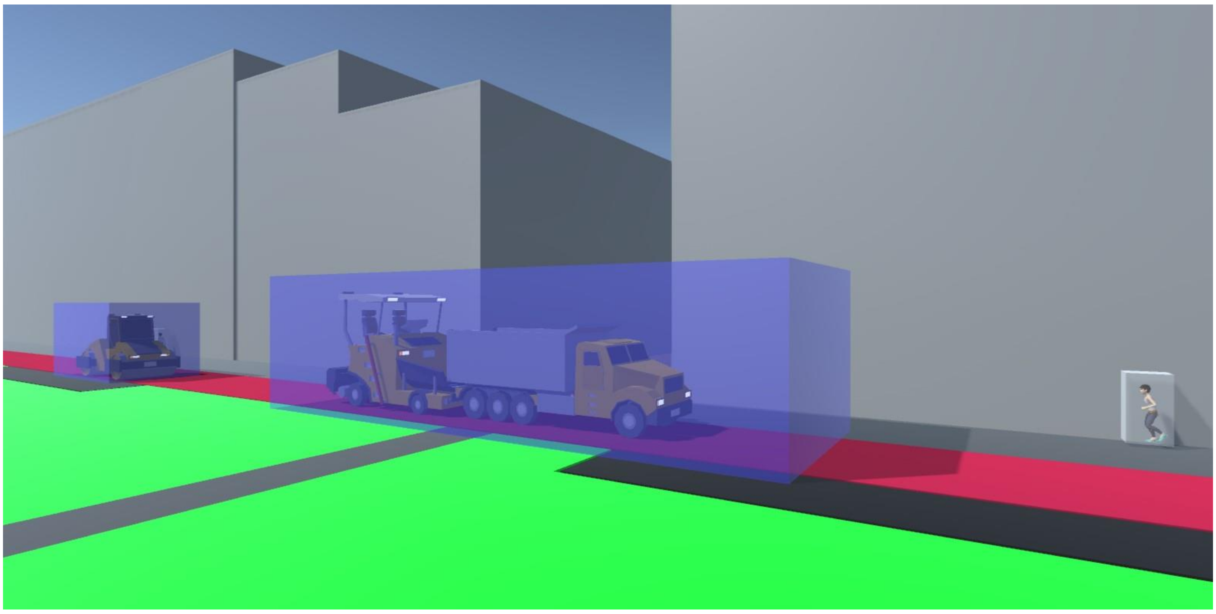


Figure 36: Paving the bicycle highway

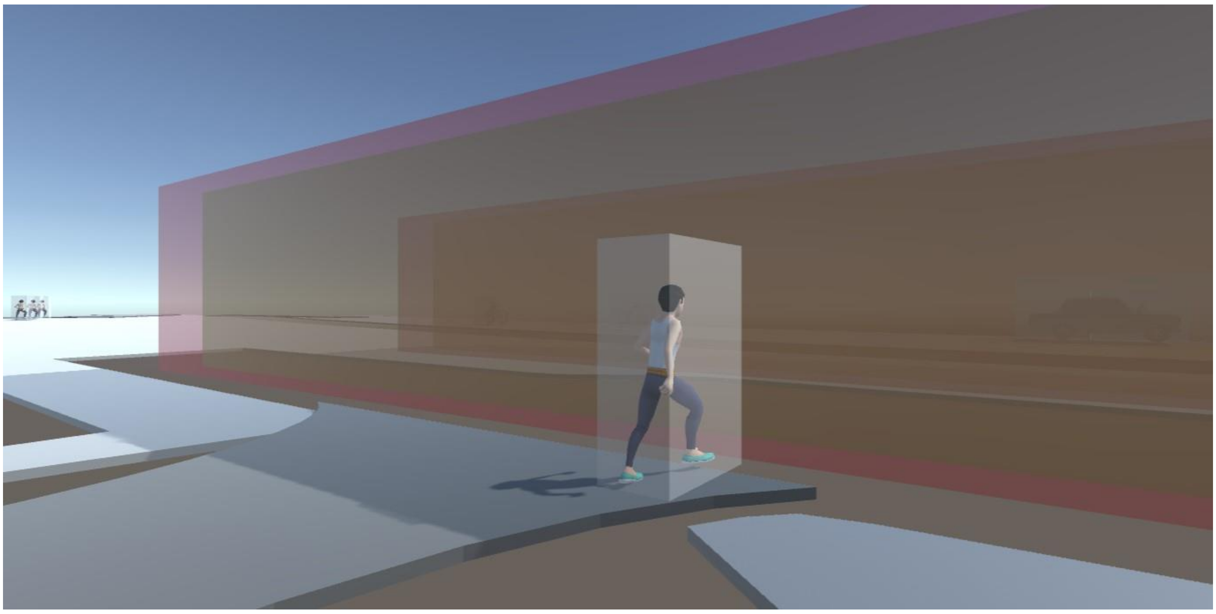


Figure 37: A pedestrian intruding into the work zone

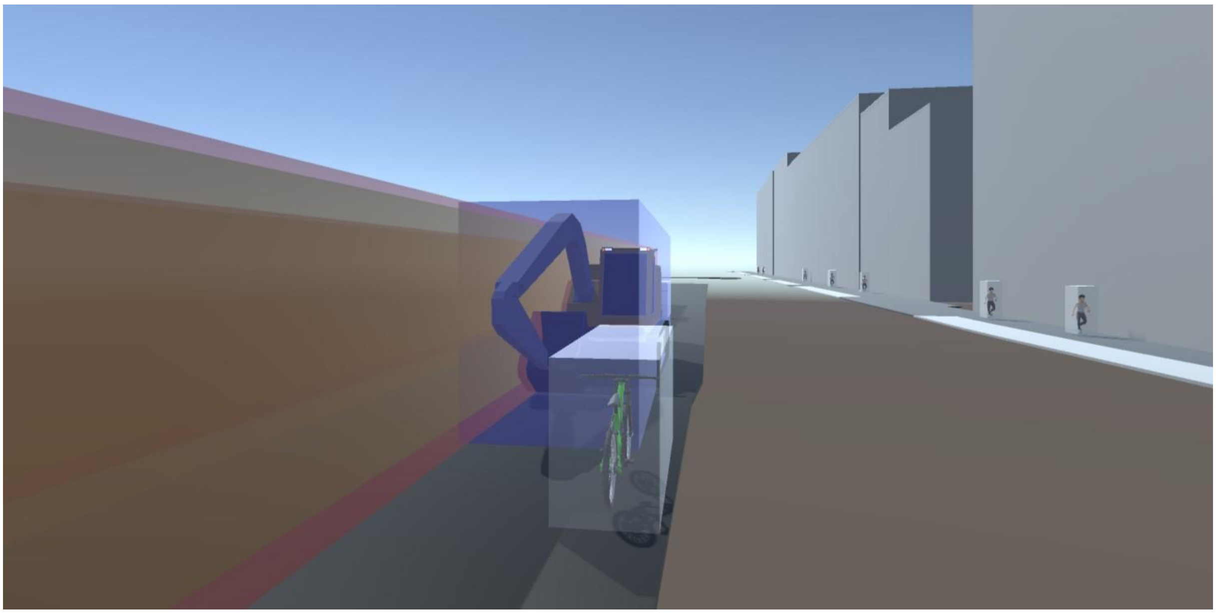


Figure 38: A collision between a cyclist and the excavator

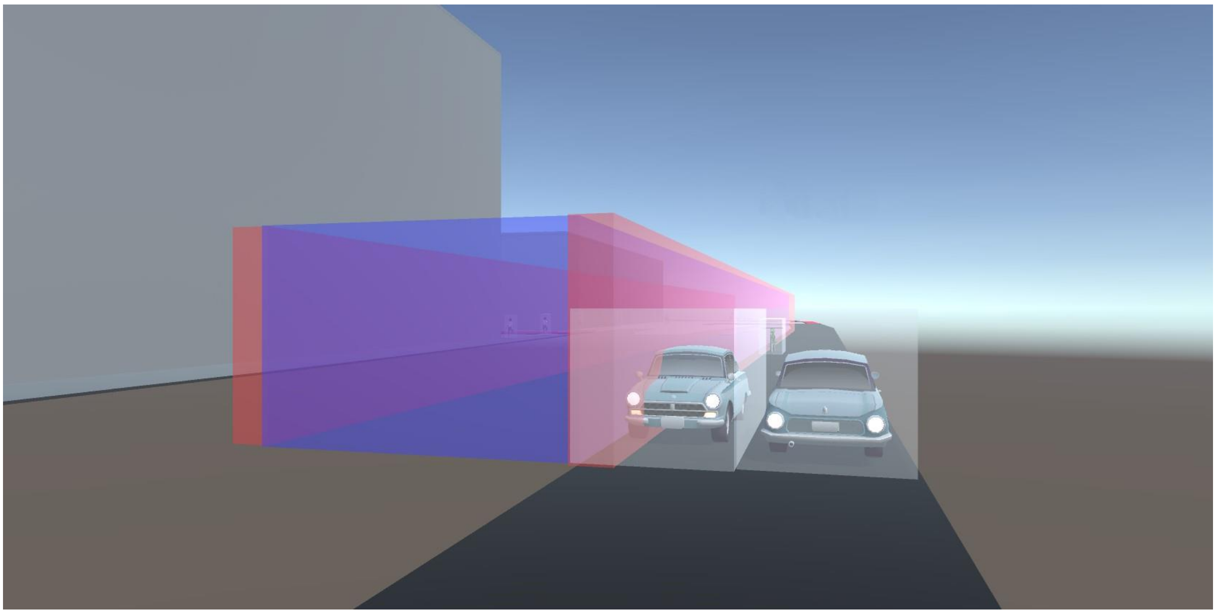


Figure 39: There is not enough space for cars to pass each other

9.3 APPENDIX III: VALIDATION OF THE TOOL

Validatie van een tool in Unity om aanrijdgevaar te detecteren

Beoordeling door de eindgebruikers

Datum: ....

Mijn functie bij Roelofs: ....

Acceptatie en adoptie

In hoeverre denkt u dat een tool die de benodigde ruimte vergelijkt met de beschikbare ruimte van toegevoegde waarde kan zijn in de ontwerpfase, dus kan een dergelijke tool een toevoeging zijn aan de huidige manier van werken?
(Deze vraag gaat dus over het algemene concept, niet over de uitvoering ervan in Unity zoals in dit afstudeeronderzoek gedaan is. Daar gaat de volgende vraag over!)

Geen toegevoegde waarde — Veel toegevoegde waarde

1	2	3	4	5	6	7	8	9	10
○	○	○	○	○	○	○	○	○	○

Opmerkingen:

Functionaliteit

In hoeverre doet de tool in Unity wat u ervan verwacht, dus vindt u dat de functies en mogelijkheden in deze tool geschikt zijn voor het controleren op aanrijdgevaar in het ontwerp van een project?

Ongeschikt — Zeer geschikt

1	2	3	4	5	6	7	8	9	10
○	○	○	○	○	○	○	○	○	○

Opmerkingen:

Gebruiksvriendelijkheid

Hoe gemakkelijk lijkt de tool u om te leren gebruiken en ermee te navigeren?

Moeilijk									Eenvoudig
1	2	3	4	5	6	7	8	9	10
○	○	○	○	○	○	○	○	○	○

Opmerkingen:

Flexibiliteit

In hoeverre denkt u dat het mogelijk is om deze tool toe te passen op verschillende scenario's en projectvereisten?

Beperkt									Flexibel
1	2	3	4	5	6	7	8	9	10
○	○	○	○	○	○	○	○	○	○

Opmerkingen: