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Using 4D CAD to visualize the impacts of highway construction on the public

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ABSTRACT

Highway construction activities have a multitude of impacts on the public that change over time and with location. In devising strategies to manage and minimize these impacts, gaining an in-depth understanding about timing and spatial extents of them is crucial. However, in practice gaining such understanding is difficult due to the complex and varying nature of the impacts. To support project planners with understanding a highway construction project's impacts upfront, we developed a 4D modeling method that visualizes the most important attributes of the impacts on the public, namely their spatial extents and their progression over time. By applying the method to support a Dutch highway expansion project, we show that, compared to 2D methods, the proposed 4D modeling method provides an integral perspective of the spatial changes of the project impacts over time that allows for the evaluation of various scenarios with relative ease.

1. Introduction

While recent years have seen advancements in defining and estimating the impacts of highway construction work on the public [1,2], little research has addressed how to best plan highway construction work to minimize these impacts. Ideally, project planners would like to consider possible impacts at the very early planning stages to ensure that their plans not only account for such impacts, but also to mitigate their effects as good as possible [3]. This is often not easily possible because impacts on health, convenience, and safety of the public can only be accounted for at the construction work activity level [4]. These difficulties are further amplified due to the linear nature of highway construction projects [5]. Unlike building projects, highway projects take place on relatively large and elongated construction sites. As a result, highway projects pass across different areas with different functions such as residential areas, business or natural parks. These, in turn, contain a wide variety of infrastructural network objects such as local roads, railways, cables and wires, and buildings such as schools, worship facilities, and hospitals. Project teams have to consider different public functions of areas surrounding the highway when establishing the impacts of highway construction work. Complicated the situation even more, as the surroundings of a highway project changes along its route, the relevant types of impacts will also change. For instance, traffic congestion, accessibility problems, and limited availability of roads have relevance for built-up commercial and residential areas, but have little relevance for natural preserves along the highway project. Hence, highway planning professionals additionally require in-depth understanding of public activities around a specific project and how these activities could be affected.

Our literature review has shown that few studies exist that suggest methods that support highway construction practitioners with gaining such an understanding. Despite the increasing and urgent need to consider public impact of construction work [6,7], the focus of most efforts is still on developing theories, methods, and tools that optimize highway construction without considering the impacts on the public (see for example [5,8–10]).

To fill this gap, this paper presents a method that allows for understanding the spatial and temporal extents of how highway construction work impacts the public. By drawing upon 4D CAD techniques that allow for the integration of spatial data visualization with construction scheduling and planning information in 3D animations [11], the method is capable of effectively visualizing the spatial and temporal attributes of different impacts. To provide illustrative evidence for the working of the method, this paper also reports the results of a case study project that implemented the method. The results from the case study show that the method supports practitioners with understanding the temporal and spatial extents of the impacts of different planning alternatives on the public by providing a dynamic and integral overview of the progression of various impacts over time and space.

The paper is structured as follows: First it derives the modeling method based on existing 4D CAD literature. It then briefly introduces our case study research methodology. Following this, the paper

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presents the research results of the application of the presented method on the case study. For this purpose, we report the results from a number of planning sessions with a project team using a 4D CAD visualizations that we generated with the proposed modeling method. The paper closes by presenting the limitations of the method, drawing conclusions, and discussing possibilities for future research.

2. Theoretical background

2.1. 4D CAD

4D CAD can be defined as the integrated visualization of 3D CAD engineering data, i.e. spatial data, and a construction schedule with purpose built modeling technology [11–14]. In recent years more and more construction projects have applied 4D CAD for an increasing number of areas, such as the visualization of designs for marketing and communication purposes, design review, cost estimating, bid preparation and procurement [14], constructability review [15], site management [16], scheduling, work-flow-based and location-based planning [13], or the identification and resolution of time-space conflicts [13]. Recently, more and more applications of such 4D visualizations have also started to integrate additional indicators into these 4D simulations, such as construction costs, project risks, or safety issues [17]. Such extended models are sometimes referred to as 5D [18] or even nD models [19].

Based on the developed technical applications, researchers have documented the advantages of using 4D CAD during construction project planning. For instance, 4D models support planners in the process of identifying potential problems before actual construction starts by visualizing a construction project and its schedule [15]. 4D models also allow for a more intuitive comprehension of the construction process than traditional 2D drawings and schedule information [12].

Although literature shows a significant increase in the number of 4D CAD applications and their advantages, so far, few studies focused on the application of 4D CAD in highway construction projects. The few studies that exist mainly focus on planning, scheduling and communication applications, or traffic planning during the construction phase (see for example [8–10]). No studies have been found in the literature that explored how 4D CAD can support project planners in understanding and mitigating the impacts of highway construction work on the public, despite their importance and the challenges project planners have with accounting for these impacts while planning highway construction work which we summarize in the next section.

2.2. Mitigating the impact of highway construction on the public

The most important impacts on the public during highway construction that have been identified in the literature are hindrance and reduced accessibility of traffic networks, noise, dust, and vibrations [7,20–22]. To devise appropriate measures to minimize these impacts, planners need to estimate the location, timing, and magnitude of impacts that are caused by planned construction work. This does not only require understanding of how different work tasks impact the public, but also of the location and type of work. Additionally, understanding of the spatial magnitude and intensity of an impact and when this impact is likely to occur is important.

By understanding possible impacts, their time of occurrence, size, magnitude, and location, planners can devise construction plans and schedules that, at one hand, allow for the operational efficiency of construction activities, and, at the same time, minimize the impact on the public. For this, planners need to make a compromise between the above two objectives. For example, during most highway expansion projects, the highway has to remain in operation. This implies that planners need to distribute necessary work in multiple work zone configurations. Large work zones, for example, cause more severe traffic hindrance [23], while too small work-zones will decrease construction productivity, which, in turn, can lead to longer duration of impacts [24]. Careful consideration of the configuration of work zones is, therefore, necessary for limiting impacts on the public while at the same time trying to achieve optimal productivity.

While devising construction plans, planners should also account for the effect a certain impact has on the functions of a certain area that surrounds the highway. Near an industrial area, the prevention of noise and dust as a result of construction work does not have high priority while the impact of construction work on traffic to and out of the industrial area might cause serious problems. On the other hand, traffic hindrances will have only limited impact on rural areas that might, however, be severely impacted by noise and vibration. Elaborating on this example, Table 1 summarizes how construction work can negatively impact different urban and rural area functions.

From the above discussion, it becomes apparent that an adequate visualization of impacts would support planners in evaluating the effects of certain possible working and planning alternatives. As most of the required knowledge for this evaluation is of spatial and temporal nature and since 4D CAD integrates the visualization of spatial and temporal information, 4D CAD is potentially an appropriate tool capable of visualizing the impacts of highway construction projects on the public. However, a 4D modeling method is required that allows planners to develop meaningful visualizations. The next section introduces such a method that we developed and tested in close collaboration with construction planners.

3. A method to model project impacts with 4D CAD

Following traditional 4D CAD modeling technique, the proposed method starts with a basic 3D model and a schedule with the different construction work tasks that are required for the specific project scope. The 3D model needs to contain information about the existing condition at the planned site of the new highway and the proposed future design of the highway. Additionally, for the method to work information about the surroundings of the project is required as input.

Using one of the commercially or freely available 4D modeling tools, planners can link these 3D model objects with the work tasks. By assigning specific sequences or start and finish dates to activities within a construction schedule, different alternative construction schedules can already be visualized in this way. Extending this generally accepted 4D modeling methodology, our method then prescribes two different techniques that allow for the specific visualization of impacts.

The first technique relies on a widely used technique in 4D CAD modeling to use additional abstract geometrical elements to visualize contextual information. Examples of such contextual visualizations are, for example, the display of construction machinery paths using lines [25–27], the use of blocks to describe surrounding buildings [28], the use of grids to allow for a better spatial orientation [29], the display of work zones and spaces using surfaces [23,30–32], or the display of possible passenger routes while visualizing the reconstruction of a subway station [15]. The here presented method prescribes the use of additional 3D surfaces to model general impacts,

Table 1
Project surroundings and different types of impacts.

Function	Important impacts
Residential	Traffic hindrance, noise, dust, vibrations
Commercial	Traffic hindrance, noise, dust, vibrations
Industrial	Traffic hindrance
Natural	Noise, dust, vibrations
Local and regional road networks	Traffic hindrance

such as noise or vibration, and their spatial extent. Using 4D software, planners can then link these surfaces to the construction tasks that cause the specific impact. Fig. 1-a shows an example of a surface that visualized the extent to which the noise caused by a specific construction activity affects the surrounding.

The size and shape of the surfaces should represent the extent of the specific impact. Initial information about the extent is often readily available. For example, manufacturers of heavy construction equipment provide data about the noise and vibration impacts caused by their products. If this information is not sufficient for the planning purpose at hand, additional expert assessments can help to adjust the available manufacturer's specification to the local conditions. Such assessments would then allow for a more exact sizing and shaping of the surfaces representing the impact on the surrounding.

The second technique we suggest provides a more detailed visualization than the use of additional surfaces. This technique prescribes that 3D structural objects such as houses, commercial buildings, and road sections are directly linked with specific construction tasks. In this way, a direct impact of a specific task on surrounding structures and buildings can be visualized. Fig. 1-b, c, and d provides examples of the application of this second visualization technique. In Fig. 1-b several buildings are highlighted that might suffer from limited accessibility due to ongoing construction work on the nearby highway. Further, Fig. 1-c and d visualizes parts of an adjacent road network that are expected to suffer from traffic hindrance due to certain construction tasks. Since this visualization technique requires the initial identification of the houses, businesses, and other structures that a particular type of impact affects, this modeling technique is more labor intensive. It requires not only the upfront gathering of information about the functions of surrounding structures from existing geographic information systems, but also the detailed linking of specific construction activities with those structures which are impacted by the construction work planned for this activity.

To enable project planners to distinguish between the different objects and surfaces, we also suggest the use of color-coding schema [33]. This schema should allow project planners to distinguish between different types of impact on the public. In addition, the use of multiple colors allows for the visualization according to the degree of severity of a single type of impact. For example, by using green, yellow, and red different noise levels can be represented. Furthermore, the application of different colors is also useful to discern different causes of a particular type of impact. For instance, each color can represent a different construction activity that causes a particular type of impact on the public, such as traffic hindrance. The selection of which colors to use is arbitrary. However, it is preferable to use colors that are easily distinguishable from each other [34]. We also suggest to limit the amount of colors used to prevent the models from becoming incomprehensible. For a more sophisticated way of choosing colors it is possible to apply automated algorithms, such as the one suggested by Chang et al. [34].

To structure the creation of 4D models and the integration of the two additional modeling techniques, we developed a standard work process. Before describing the process, it is noteworthy that we intentionally did not include any information about a possible distribution of the depicted process steps to different roles in the project team. We chose to not include this information mainly because we believe that the effective organization of the process should be dealt with on a project by project basis, adjusting the modeling effort to specific prevailing project conditions and personal skills of the available staff on a specific project [35]. Fig. 2 provides a graphical overview of the developed process. The figure shows that the modeling method requires different types of inputs. These consist of

- *Geographical and location related data about the existing condition of the area*. These data can be usually obtained from geographic information systems or from existing design documentation. Important geographical data are, for example, the topography of the terrain surrounding the project or information about the surrounding built environment.
- *Highway design data*. These data should include information about the new alignment of the highway, its exact geometrical properties, and its structural composition. These data can usually be obtained from the design documentation of the project, for example, from the tender documents.
- *Construction activity related data*. These data should include information about the project phasing and a construction schedule that covers the road section that is modeled. Information about the possible impact of different construction methods on the public and the spatial extents of these impacts are also particularly important input data for the proposed modeling process.

After gathering these data and, if necessary, converting them for use with specific 4D modeling software, the first of five modeling sub-processes can take place. This is the creation of the basic 3D model which consists of 3D objects representing the existing and proposed new highway structure that is subject to construction work, the terrain and traffic network surrounding the project, and the surrounding built environment. Next, depending on the visualization needs and type of impact modelers can choose one or both of the two special visualization techniques for each impact that is to be visualized. After the required impacts are visualized using a combination of the two techniques, the additional 3D objects can be integrated with the initial 3D object of the highway project and its environment. The next step involves the configuration of color codes to be able to discern different construction activities and their impacts. Finally, the tasks in the construction schedule and the objects and surfaces of the 3D model can be linked to the 4D model that planners can then use to quickly evaluate different construction sequences by changing the relations between tasks and their start and end dates.

4. Development and testing of the 4D CAD method

4.1. Research method

We developed and tested the above described 4D CAD modeling method through an ethnographic action research effort [36] that we conducted with a large Dutch engineering firm. Ethnographic action research proposes to implement information systems, such as the here presented 4D CAD method, in small iterative cycles of close observation of work practices of a project team and the consecutive implementation of the information system according to the outcomes of the observations. In this way, empirical testing and further development of new systems is coupled closely and guarantees the implementation of methods that can truly support work practice.

For the purpose of testing the developed method, we applied it together with a tender team to prepare a bid for the expansion of a major Dutch highway extension project. The goal of the project for which the team prepared the tender bid, was to increase the capacity of a 30 km long highway stretch by adding extra lanes and reconstructing parts of the local road network. To realize the added capacity, the work constituted the partial relocation of the highways route, reconstruction of several viaducts and underpasses, and the construction of noise barriers, traffic signs, information systems, and ecological facilities.

Following Yin's [37] purposeful case selection strategy, we selected this project for three specific reasons. The first reason was that the to be expanded stretch of highway was surrounded by different residential, industrial, and natural areas. This provided an excellent context to test the modeling method with respect to how it supports planners with understanding the spatial and temporal extents of how construction work impacts different types of surroundings. The second reason for selection was that most highway projects in

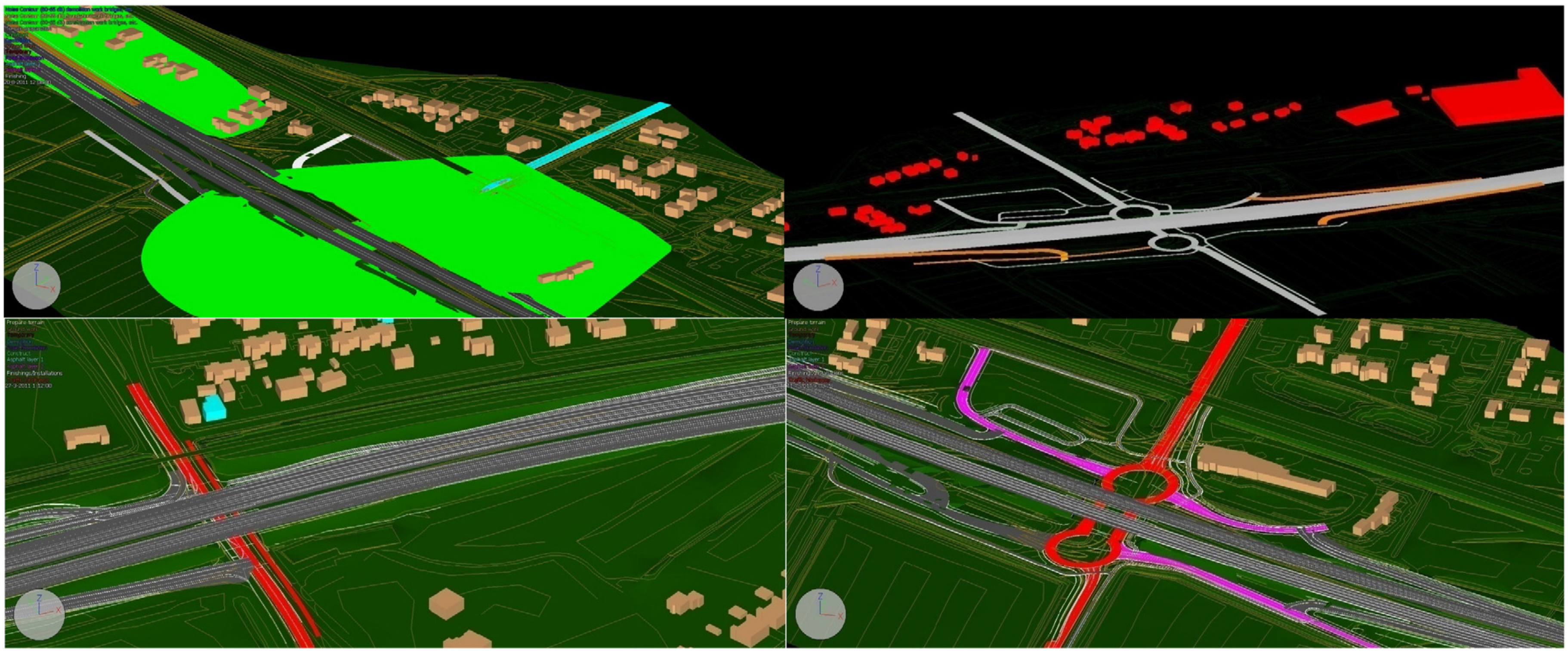

Fig. 1. Snapshots from 4D models visualizing the spatial extents of different impacts of construction work on the public. Upper–Left (a): Use of surfaces to visualize the extent of noise impact on the surrounding area. Upper–Right (b): Highlighting of specific affected buildings in the area. Lower–Left (c) and Lower–Right (d): Highlighting of parts of an affected traffic network.

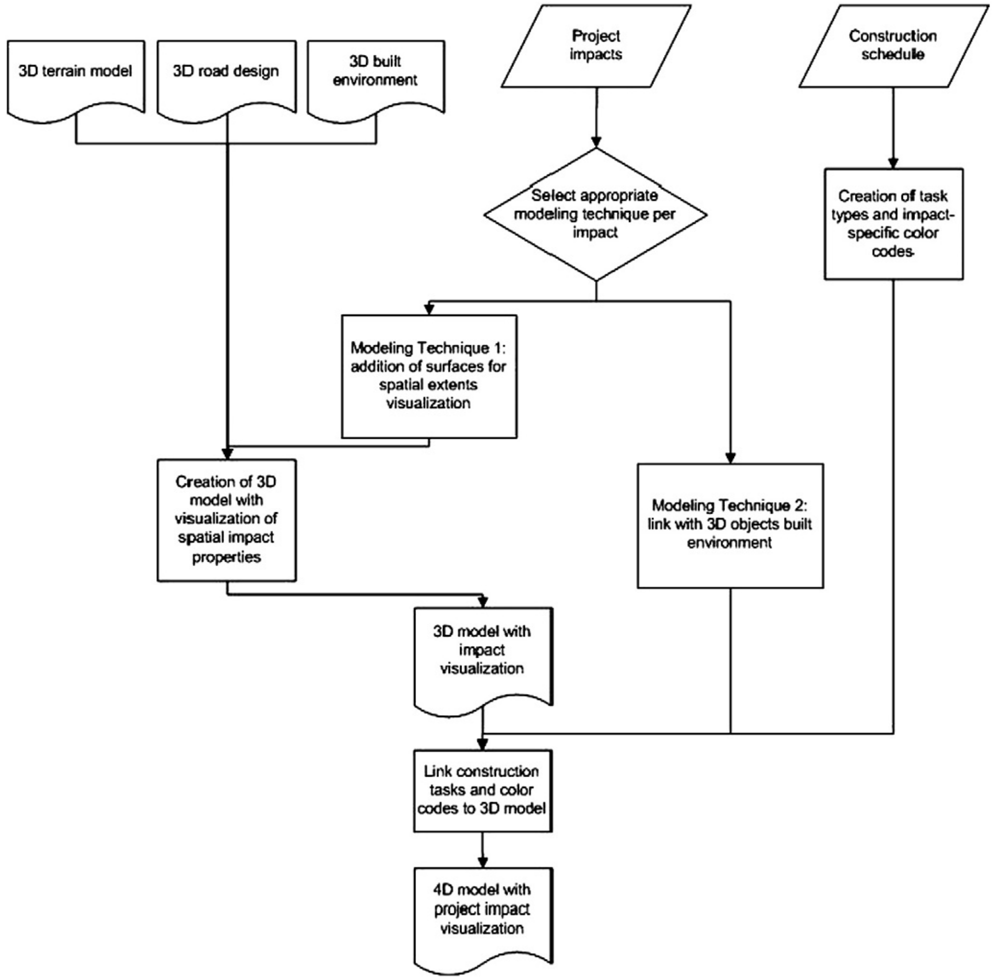

Fig. 2. Schematic process diagram of the proposed 4D modeling method.

industrial nations are by now concerned with the expansion of existing infrastructure. Hence, it is likely that challenges encountered on this project are typical for many highway construction projects in developed countries worldwide. We expect that the findings from this case study can be generalized broadly. The final reason for selection was that one of the clients' criteria for the bid evaluation was the inclusion of feasible strategies to minimize the impact of construction work on the public. Devising such strategies had, therefore, a high priority for the project team. Hence, project team members were highly motivated to work together with us throughout the research.

The tender team itself was comprised of approximately twenty professional engineers of different expertise levels working together within a specifically dedicated office throughout the preparation of the tender. The exact composition of the team shifted throughout the research phase as different specialists were involved at different times. The tender team was also supported by a dedicated three dimensional modeling specialist that supported the engineers with different models of the project. This modeling specialist also developed the final 4D models using the method presented in the paper.

To conduct the actual research work, the first author of this paper spent every working day at the tender team's office throughout the complete tender preparation phase that lasted for about six months. Before entering the field this researcher familiarized himself with existing technologies to generate 4D models, their functionality, and best application practices. The researcher worked through official tutorials of the software vendors and consulted software experts, both at his university and at the company of his host project team. Furthermore, the researcher trained himself in formal participatory research methodology. This initial training program ensured that he was able to enter the field with a good basic knowledge that, together with the close collaboration with the project team throughout the research effort, allowed him to gain in depth insights about the decision making routines of the project team. Additionally, the approach allowed him to collect detailed information about the use and usefulness of the implemented 4D model to support these decision making processes. The first author then regularly discussed his day-to-day insights with the other authors. These discussions allowed us then to jointly refine the method and to validate its usefulness in supporting the practitioners working on the project. In the end, the chosen research methodology helped us to gain a much richer understanding about the practical applicability of the method than it would have been possible, for example, through an experimental validation within a controlled setting.

To reduce the modeling scope, we focused our efforts on a specific section of the overall project for which we expected especially complicated inter-dependencies between construction work and the public. The selected road section was characterized by surrounding built-up areas of the main types summarized in Table 1. It was also expected that construction work in this section would significantly impact important local and regional roads around the highway. Additionally, the client designated this highway section for bidding parties to showcase a more detailed elaboration of plans and strategies to minimize the project impacts which again helped to integrate the case study research in the prevailing work tasks of the project team.

4.2. Development of the 4D CAD modeling method

We started the development effort with a number of work sessions with members of the tender team during which we identified three initial elements that the project was interested in exploring with the use of a 4D CAD model:

- The time of occurrence, location, and size of construction work zones to understand traffic hindrance on the highway,
- The accessibility to key areas around the highway, such as hospitals and large office complexes, and
- The availability of the underlying road network during the construction phase.

We then developed a first 4D CAD model using the commercial available 4D modeling package Navisworks from Autodesk. As input for the model we used information from an existing 3D model that the project team was maintaining in Autodesk's software AutoCAD Civil 3D. This initial model included the old highway prior to construction based on available GIS data. The initial model also contained the proposed design of the new stretch of highway. Using this prototypical software architecture, we modeled the above listed items of concern using the direct visualization technique that links construction activities with 3D objects representing actual structures, such as roads and buildings. We formalized the steps that we conducted by developing a first version of the modeling method that, at this state, only included the direct impact visualization method.

Following the iterative action research cycle, we then used the generated 4D CAD model during three workshops with tender team members to determine the potential of the 4D CAD model generated. During these workshops we generated and visualized different alternatives to schedule the necessary construction work by changing construction task durations and task relations. By updating the underlying construction schedule used in the 4D CAD models, we were then able to immediately visualize changes in construction plans. The participants of the work shop discussed the impacts of each new alternative and suggested improvements to the schedule. These improvements, in turn, were then directly incorporated in the 4D model and visualized again. By optimizing the schedule in this way, we supported the tender team with iteratively minimizing the expected impacts of construction work on the public.

To trace the benefits the model offered during these workshops, we took detailed notes of all statements the practitioners made about how the 4D CAD models helped them to acquire knowledge of the impacts on the public and how practitioners used this knowledge to decide on strategies and alternatives. Additionally, we also recorded all ideas for further possible uses of the 4D CAD models. Based on our notes, we then extended the modeling method with the second visualization type of linking construction tasks to purposefully modeled surfaces to represent the extent of an impact over an area. We then updated the existing 4D CAD model following the refined method by including a number of surfaces representing different noise and vibration levels that were expected to occur during the planned construction work. Again we used this second version of the model in a series of three workshops with practitioners to test and analyze how well 4D CAD models generated with the method work.

During this new round of workshops the project team members intensively used the generated 4D CAD model. Hence, the second workshop round provided detailed evidence for the usefulness of the 4D CAD model generated with the method. For example, in one of these discussions workshop participants used the 4D model to support their discussion about noise levels caused by various construction activities. Using the possibility of the 4D model to visualize noise levels with color-coded surfaces linked to tasks in the construction schedule the workshop participants became aware that in the original schedule they had planned a number of high noise-producing activities close to a residential area to take place at the same time. This concurrent scheduling of activities would have compounded the negative impacts of the construction work in this area. After realizing the shortcomings of their initial schedule, tender team members started to directly alter the construction schedule and used updated versions of the 4D model to evaluate a number of possible schedule alternatives. In the end, the tender team was able to improve their planned schedule by distributing construction activities that caused high noise, thus reducing the overall impact of the construction work.

4.3. Summary of the method evaluation

To provide readers with an overview of the main findings derived from the participatory research effort, we provide exemplary verbatim statements from members of the tender team in Tables 2 and 3 that we recorded during the workshops. Table 2 compiles statements that show the direct applicability of the 4D model generated with the method to support the discussions during the workshops. Table 3 summarizes statements that workshop participants voiced about possible applications of the 4D model beyond its use during the workshop sessions.

The statements in Table 2 show that practitioners see advantages in applying the modeling method to understand the spatial and temporal aspects of impacts on the public caused by highway construction work. The statements suggest that practitioners felt that the 4D model generated using the proposed modeling method supported them in their effort to optimize construction schedules. This potential becomes also evident from a number of discussions about how to best optimize construction schedules. Overall, these statements show that the possibility to review impacts in a single model that combines design and schedule and that allows for the easy generation of different scenarios was seen as particular advantage of the 4D modeling method. The findings from the workshop suggest that the 4D modeling method can provide easily interpretable and multi-functional models, and is able to better fulfill the needs of practitioners with regard to obtaining insight in the impacts of highway projects than traditional 2D based methods.

Beyond the direct application of the models during the workshops, Table 3 additionally shows that participants suggested possible applications of 4D models that we were not able to test and observe on this project. Tender team members, for example, referred to the ability of the modeling method to integrally evaluate the effects of different design and scheduling solutions on the impacts of the project. Furthermore, tender team members also suggested that the models

Table 2
Statements showing that the model generated with the method provided planners with understanding and insights about impacts.

"The models might help us to understand where certain types of impacts occur and how this, and the severity of the impacts, changes over time."
"The models give a dynamic insight in how impacts change as the project schedule changes and this insight might give us an edge in the competition to win points for this part of the tender. It might also aid us in decision-making with regard to the best way of dealing with different types of impacts."
"By bringing the design and scheduling work together in a single model, we will be able to check whether the proposed design and schedule is appropriate with regard to the impacts it will have on the project surroundings.
"Current traditional methods involve us using the length profile of the project and marking areas on these drawings that are sensitive to certain types of impact. What this lacks is the ability to visualize changes over time."
"With 4D modeling we can broaden the scope in which we consider the impacts on the public, and, from what I have seen, flexibly evaluate different scenarios. Currently we mostly view these projects from the perspective of the highway itself, but taking the surroundings of the project and underlying road network into account is becoming increasingly important."
"Traditional methods lack the possibility of an integral overview, because you have to evaluate the drawings and project schedule separately, which means that a lot of useful information is lost."

Table 3
Statements summarizing the ideas of the professionals to use the generated 4D models beyond its application in the workshop.

"4D models are also advantageous over 2D methods because they are easier to understand by laymen than traditional technical drawings."
"We could very well use these models as a part of the plans we will deliver to the client for the final bid."
"These models are also a useful tool for communication in the realization phase."
"We could use the models during meetings with local residents and pressure groups to communicate the plans and give these parties an advanced notice when certain types of impact are planned to occur."
"It would be nice if we could link these models to a database so we can automatically send messages to local residents and businesses indicating when they will have some form of hindrance due to construction work."
"By visualizing the project impact this way, we might evaluate how and when different impacts occur by changing the schedule or limiting simultaneous work in certain areas."
"Once the contract is awarded, we have to create more detail in our project strategy before implementation in practice is possible. Because of the easy interpretation of the models, we can use them to discuss issues with regard to minimizing impacts on the public with the client. Detailed 4D models may prove an effective tool to communicate these issues between parties and optimize chosen alternatives."

may be suitable to support communicating with parties outside the project team. This suggests that practitioners were already seeking ways to create and use 4D models that allows them to do their work better and more efficiently. Overall, these findings show that practitioners perceived the 4D model generated using the method as very beneficial.

5. Discussion

The research described in this paper provides a modeling method that views highway projects as an integral part of the area in which they are constructed. In doing so, the described work represents a pioneering attempt to develop a modeling method that allows for the dynamic visualization of possible impacts of highway construction work on the public. With this focus, the presented modeling method not only contributes to the highway construction project planning, but also to 4D and 5D CAD modeling theory in two distinct ways. For one, currently, the majority of 4D CAD research focuses on vertical building construction, rather than on horizontal linear construction work, such as highway projects. Linear construction work is often highly complex and challenging [8], in particular, due to its wider impact on its surroundings. This study is therefore one of the few studies that focuses on developing 4D CAD systems that allow for the better planning for horizontal construction work. Hence, the presented methods complement the larger body of work that explores how to utilize 4D visualization techniques to support construction planning [38]. Additionally, the method in this study, provides a stepping stone to further understanding of how to visualize non-geometric information meaningfully in space and time. With the advent of more and more information models (for an example see [39]) – often called 5D or nD models – that combine different information with geometrical design models of facilities, visualization methods for non-geometrical information will become more and more important. Our study contributes to this discussion, by providing a method of how to meaningfully visualize information stored in multi-dimensional data models that is applicable to the case of visualizing highway reconstruction projects.

Next to these more general contributions to 4D modeling theory, the developed method formalizes the use of two specific 4D visualization techniques:

- The use of color-coded surfaces within 4D models for the purpose of indicating the location and extents of various types of impacts to allow practitioners to grasp the spatial extent of possible impacts and
- The use of 3D objects representing other road structures or facilities in the proximity of the highway to provide a more detailed image of where impacts occur.

Through developing and testing the method in close collaboration with practitioners, we provide evidence that the method and the two visualization techniques indeed provide planning professionals with a better understanding of when and how areas surrounding the project might be affected by planned construction activity. Beyond the specific implementation to visualize the impact of highway construction work on the public, these techniques are applicable for developing 4D models to support a wide range of construction planning tasks that require the generation of understanding about temporal phenomena in a construction site's surrounding. Our study, hence, confirms the findings of previous research (see for example [5,8–10]) about the practical applicability of 4D models for the area of highway construction planning.

The method presented in our study can also be applicable to make different simulation outcomes available during construction planning activities. In fact, the visualization of the availability of the underlying road network during the construction phase was based on a traffic simulation of the area around the construction site. By visualizing the outcomes of the simulation in space and time during the construction work, the outcomes could be accounted for while planning the sequence of the construction work. The same holds for the visualizations of noise and vibration impacts that are also outcomes from more sophisticated simulations of construction plant and work activities. Overall, the method presented provides a first stepping stone to integrate sophisticated simulations into the planning practice of construction professionals. The method can, for example, be used to visualize the outcomes of the large number of recently proposed traffic simulation algorithms [40–47].

With these theoretical contributions, we expect that the modeling method has the potential to impact practical highway construction planning work in a number of areas. The 4D modeling method provides practitioners with a tool to visualize and evaluate impacts on the public more easily than the traditional methods that mainly rely on the mark-up of a number of construction staging drawings in two dimensions. The proposed method also allows for the integrated assessment of the temporal and spatial aspects of highway project impacts and reduces the possibility of errors in interpretation. Furthermore, once basic 4D models have been created, updates are readily carried out, and, with minor adjustments, the visualization of additional types of impact on the public is possible. The modeling method provides the ability to work out many different project scenarios and review changes in the project impacts without the need to create completely new drawings or schedules. In this way, the modeling method provides practitioners with a means to reduce the time spent on creating drawings, schedules, and other related planning media and allows more time to be spent on evaluating scenarios and alternatives. Overall, we expect that the method has the potential to improve the quality of the decision-making process to define sound construction strategies that minimize the impact of construction work on the public.

6. Conclusion and outlook

Managing the impacts that a highway project has on the public is an important part of highway construction planning. Finding a schedule that minimizes impacts is a multi-criteria decision-making problem that requires trade-offs between possible impacts and their spatial and temporal magnitude. Additionally, highway projects are linear projects along which the characteristics of the surroundings change. Hence, the effect that different types of impact have on the surrounding public also changes. Devising construction schedules that minimize the impact of construction work on the public is a complex and knowledge intensive task.

To help planners to gain the necessary understanding about the temporal and spatial extents of impacts that is required during such complex scheduling tasks, we developed a 4D modeling method that visualizes possible impacts and their magnitude in relation to the surrounding of a highway project. The method uses two specific modeling techniques. The first modeling technique adds surfaces to a 3D model to visualize the area that a particular impact affects. The second technique uses 3D representations of actual structures and links construction activities that might cause certain types of impact related to the specific structure to these representations. By applying color-coding to the surfaces and 3D objects, the method can also visualize the various types of impacts and their magnitudes. We successfully applied the method by developing and using a 4D model for a highway project in the Netherlands. The feedback received during the use of the model shows that the method is capable of effectively visualizing highway project impacts and providing knowledge about these impacts.

Despite this initial successful application of the method, there are also some limitations in the method that provide possibilities for improvement and augmentation. First, currently the generated 4D models can only show a small number of impacts within one model. The addition of too many impact visualizations makes the 4D models quickly too cluttered to be understandable. Hence, future research should devise techniques that allow for the visualization of multiple types of impact in a single model without compromising its intelligibility and representational clarity. A second possibility for researchers to build upon the work described here is to integrate the modeling method tighter with simulation tools. Currently, the method can only be used to statically model the outcomes of simulations. True round-trip analyzes are not possible. For example, currently it is only possible to visualize different levels of traffic congestion that have been calculated with a traffic simulation tool before the actual generation of 4D models. An integration of traffic simulation models with the proposed method would allow for the dynamic visualization of traffic hindrance according to changes in the scheduled sequence. Of course, traffic is not the only impact that can be simulated. Overall, the method actually might be a first stepping stone towards tools that allow for the dynamic visualization of the outputs of several simulations in one 4D visualization. Such a tool would allow for the holistic understanding of the temporal and spatial extents of impacts of highway construction projects and for truly dynamic multi-criteria decision around a large number of construction scheduling alternatives. Such methods would also allow for the dynamic update of simulation inputs according to chosen construction sequencing options.

Concluding the paper, the modeling method described offers practitioners an effective alternative to current 2D methods that is relatively easy to use and comprehend. By using a visualization technique that is applicable to several types of impacts, knowledge about the complex nature of these impacts becomes more easily obtainable. Additionally, the proposed method lends itself well for the evaluation of different scheduling alternatives because initially created 4D models are easily adjustable. We believe and illustratively showed that the method already has the potential to offer highway construction planners a clear picture of the impacts of construction work on the public and allows for the joint minimization of these impacts. Additionally, the developed modeling method provides ample opportunity for augmentation with other impact evaluation techniques such as dynamic simulation tools which can further improve the practical value of the method in the future.

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