IFC-based linking of the risk management process using a building data model

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Abstract. A vital element in working with BIM are standardised exchange formats that enable the exchange of information from digital building models between different software solutions and project participants. In this context, the Industry Foundation Classes (IFC) defined in DIN EN ISO 16739 represent a central standard for implementing the open exchange of information. Although approaches for integrating risk management are already available in IFC, they do not sufficiently reflect the needs of the construction industry. In order to increase project quality through risk management and the universal application of the Building Information Modelling (BIM) method, it is essential to map the generally valid information on the risk management process in IFC. The following article thus presents starting points for the further integration of risk management in IFC. The aim is to link all relevant risk information in a digital building model through an analysis and the development of an approach.

1. Initial situation: Risk management and BIM

In 2015, the German Federal Ministry of Transport and Digital Infrastructure (BMVI) included risk management - along with nine other aspects - in a 10-point plan for major building projects in Germany [1]. An analysis of the misalignment of numerous major projects revealed that risk management is a central control variable for leading construction projects to success [1]. While the application of risk management is a standard practice for other industries, the construction industry still does not seem to place enough attention on risk management. In 2019, a study conducted by the University of Wuppertal among 249 german construction companies and public contracting authorities revealed that around two-thirds of the companies surveyed - despite the commission's findings around the development of the 10-point plan - do not apply a risk strategy. Projects do not systematically track risks and do not incorporate lessons learned from projects into follow-up projects [2].

With regard to the frequently criticised delays and cost increases in construction projects, the industry misses the opportunity to recognise negative deviations from project goals at an early stage and to take countermeasures in time due to the negligent handling of risk management. In particular, inefficient documentation and company-internal isolated solutions for risk management are cited by a large number of companies in the study by the University of Wuppertal as a reason for the inadequate application of risk management in ongoing work processes [2]. Especially with regard to this aspect, the BIM method and the associated digital linking of information in a project offers potential for the implementation of risk management information [3]. By digitally linking risk information, isolated solutions can be avoided, the associated processes are made more efficient and the attractiveness of dealing with risks increases for all project members.

A key feature of working with BIM are standardised exchange formats that enable the exchange of digital information between different software solutions and project participants [4]. In this context, the Industry Foundation Classes (IFC) defined in DIN EN ISO 16739 represent a central standard for implementing the open exchange of information [4] [5]. With the help of IFC, information is standardised and defined for use with BIM to ensure the sufficiency and accuracy of information exchange between the various stakeholders [6]. Approaches for integrating risk management are already available in IFC. However, a more detailed analysis shows that the approaches standardised in IFC do actually not cover the needs of the construction industry sufficiently. In addition to that, the existing approaches focusses particularly on occupational safety [4]. In contrast to the current approach, the focus should be on the information needed within the steps of the ISO risk management process and not limit the information to a specific topic. Therefore, this paper addresses this issue and presents starting points for the further integration of risk management in IFC and digital building models. Here the focus is on the analysis and presentation of possibilities for integrating the relevant information on risk management in IFC.

2. Framework and methodology

This paper presents a three-step methodological procedure to develop an approach for integrating risk management in IFC. The three steps are divided into a literature analysis (step one), a gap analysis (step two) and the development of relevant processes and their validation (step three).

Step one (see chapter 3), the analysis of the current status, examines the processes of risk management on the basis of a literature analysis. This results in the to-be processes of the construction risk management. These processes are validated by survey results and semi-structured expert interviews with 19 practical users of risk management in german construction projects. Finally this results in the as-is status, which can be compared with the to-be processes.

Based on the process analysis, an analysis of the differences between to-be and as-is processes is carried out in step two (see chapter 4). With the help of an analysis based on the gap analysis, that is common in business administration. A gap analysis first determines goals, considers the as-is state, assesses strategic and operational gaps and identifies measures to close these gaps. Finally, milestones are defined to review these measures [7]. For this purpose, this paper compares the information required for the to-be process for risk management with the information that are already available for risk management with open exchange formats (here IFC). This is done through the exemplary application of the PSet_Risk to a building data model. The result is an overview of needs for integrating risk management information in IFC. A solution proposal is developed for this gap. Specialised tools such as software solutions for automated linking of model and data are not considered in depth in this paper. Instead, it is about the possible solutions of the IFC file format and how they harmonise with systematic risk management.

In step three (see chapter 5), this paper validates the results of the exemplary application and the development of the current status quo. Therefore workshops with risk managers and executives of the construction industry were carrried out by using the method of the "World-Cafe" [8]. The aforementioned methodological approach is summarised in Fig. 1:

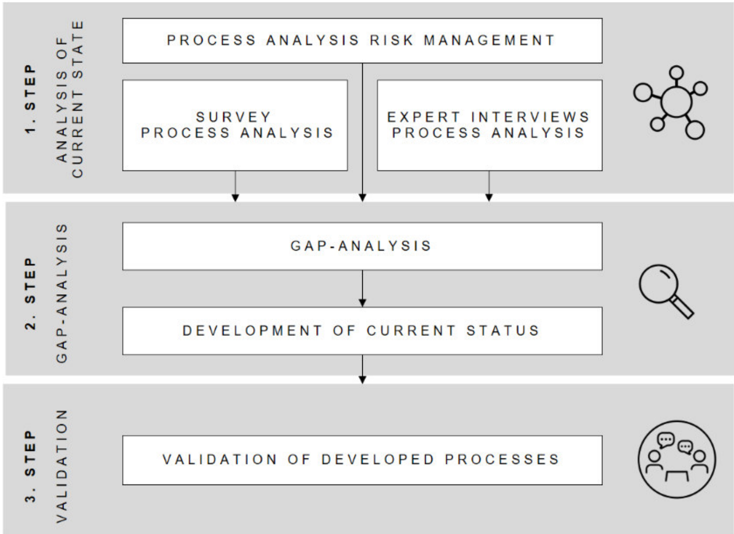

Figure 1. Flowchart of the methodical approach Source: own illustration

3. Analysis of the application of BIM in risk management

BIM describes a method that integrates and links all relevant data of an asset in a digital building model over the entire life cycle (from conception, planning and realisation to use and deconstruction) [9] [5].

Initial approaches to integrate BIM and risk management already exist in the literature [10] [11] [12]. In this paper risk management is understood as "coordinated activities to guide and control an organisation with regard to risks" [13]. In the aforementioned initial integration approaches, however, the focus is regularly on ensuring occupational safety and health, with the result that a comprehensive consideration is not carried out. As the definition of risk management shows, the process does not refer to a single special topic - such as occupational health and safety - but to all risks that prevent a company from implementing its corporate strategy [14]. Therefore, for an integration of risk management in IFC, there should be no thematic restrictions regarding the origin of the risks. With this in mind, this paper first presents an analysis of the status quo regarding the linking of BIM and risk management. Subsequently, a process analysis is carried out to show the possibilities for the successful exchange of information during the risk management process using the BIM method. Based on this, the results of the process analysis are validated.

3.1. Fundamentals for the integration of BIM and risk management

Three principles are important for the application of BIM in the context of the risk management process. The principles Integration, [3] [2], Dynamics [3] and Accuracy [6] ensure a smooth application process. The integration of digital data into the respective process steps during project processing is imperative. This allows an information basis to be built up over the entire life cycle of the property and the information can be accessed by the respective parties involved [15]. Furthermore, the exchange of information in the individual phases and between the different users is facilitated.

Risk management must be understood as an integrated process in order to form an effective project management and controlling instrument [13]. The various work processes and their contents of risk management are interdependent and influence each other [2]. Furthermore, due to the constant change in the information base, all processes must be able to adapt and develop dynamically.

By using the BIM method, the aforementioned processes can be made more transparent and effective with the transfer of information to the risk management process:

1. Precise information about the entire project are necessary prerequisites for the application of risk management [16]. BIM helps to structure the information growth over the entire life cycle of a construction project, enabling the knowledge to be used for process improvements in the company and knowledge gain for subsequent projects [17].

2. The exact project status is essential for successfully applied risk management [3]. Through BIM, the as-is status of a construction project is recorded and the information is available digitally and visually.

3. The BIM method makes changes in projects digitally readable and adaptable. Due to open standards, the relevant information can be exchanged between the parties involved.

3.2. Process analysis of risk management

In order to analyse the information needs of risk management for integration into the BIM method and for open exchange formats, a process analysis of risk management is necessary.

The basis for the implementation of risk management is the company's internal process definition. The risk management process is defined within the company and includes the predefined parameters of the risk management strategy. The management is responsible for the process.

The risk management process describes the individual steps of risk management in project processing. As in the risk management strategy, the responsibilities, risk tolerance limits, communication channels, risk management methods and documentation methods are defined for each process step [18]. The risk management process, which must always be kept up to date, is divided into four main steps. These consist of the steps risk identification, risk assessment, risk control and risk monitoring. Continuous controlling, careful documentation, regular communication and consultation complete the control loop of risk management [19]. In a construction company, the steps start in the realisation phase and run through all service phases of the Fee Structure for Architects and Engineers (HOAI). The HOAI is a legal regulation issued by the German Federal Government to regulate the fees for architectural and engineering services in Germany and describes nine service phases throughout the lifecycle of a building.

The risk management process is a constantly repeating process. DIN ISO 31000 provides the process structure for risk management shown in Fig. 2 [18]. DIN ISO 31000 for risk management does not define any parameters for application to an IFC file. Only the common basic terms and the elements of the risk management system are presented here.

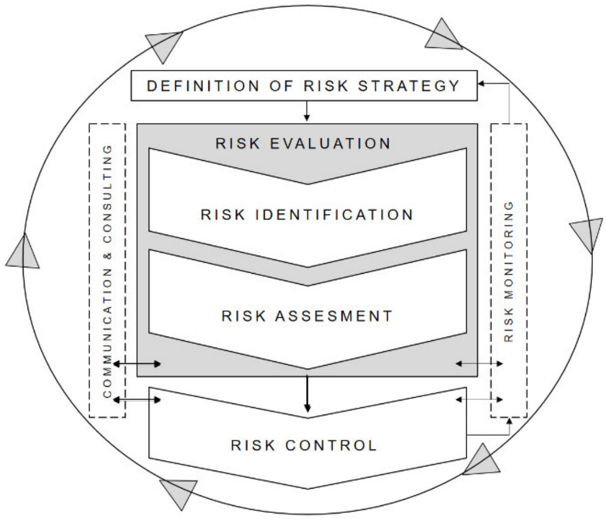

Figure 2. Risk Management Process Source: own illustration based on DIN ISO 31000

A prerequisite for linking information from the risk management process with a building data model using IFC is the specification of the relevant informations for risk management. An analysis of research on risk management, BIM and IFC showed that the theoretical risk management process of identification, assessment, control and monitoring is partly implemented in the construction industry, but at the same time there is no precise overview of which information is needed when, for what and by whom [20]. The research project 'BIM-based risk management' at the University of Wuppertal therefore breaks down the risk management process on an information basis and shows at which point in the risk management process which information flows in, who created it and for which steps it in turn serves as input [20]. The basis for this was provided by the semi-structured expert interviews conducted as part of the project and the survey (cf. section 3.3). Fig. 3 shows the relevant input and output information for the identification process step.

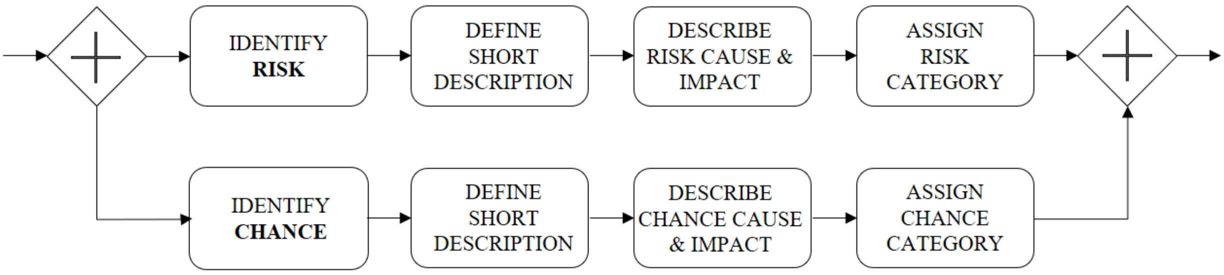

Figure 3. Process step of risk and chance identification Source: own illustration

As illustrated above, within the step of risk identification, risks and chances that could occur in the project are listed. Risks represent negative deviations from project goals, chances represent positive deviations. Regardless of whether an aspect is identified as risk or chance, following the identification, the risk or chance is defined by a short description that ensures easy recognition within the following steps. In the next step, the cause and impact of the risk or chance are demarcated. Risk categories such as technical, financial or legal support the identification by offering indications of the areas in which risks or chances could occur.

These evaluations represent the first step in linking risk management with BIM. The identified informations that are relevant for the risk management process should be mappable in the digital building model via IFC in order to integrate the risk management process into it. Only through a complete mapping of the risk informations, the model supports controlling the risks and redundancies by storing informations can be avoided.

3.3. *Results of survey and expert interviews on process analysis*

The identified BIM information from the process analysis was then validated using surveys and expert interviews. The results presented below are based on the survey on risk management in the construction industry implemented in 2019 among 249 construction companies and semi-structured expert interviews with 19 risk managers, which paint a clear picture of the current application of risk management in construction companies within Germany.

Regarding the flow of information and documentation as well as the level of detail in the implementation of risk management, different degrees of professionalisation can be observed in the construction companies. Risk assessment is largely intuitive and shaped by the experience of the individual employee. After project completion, the knowledge gained is usually only passed on to selected employees in discussions at the communication level. Hardly any company carries out a systematic evaluation of the previous risk list or a systematic continuation and feedback into its system. This means that the potential of risk management is not fully utilised.

The analysis reveals three main shortcomings in the current application of risk management:

1. empirical data on risks from completed projects is not evaluated, so that an overview of typical risks and their probabilities is lacking;

2. the exact functioning of the risk management process and its application in construction projects is often not clear; and

3. there is a lack of tools to document risk management across all processes of the risk management cycle and to evaluate it for follow-up projects.

In addition, the analysis of various software tools in the field of risk management and BIM did not find a solution for the application of risk management using BIM at the building component level. In this respect, the conclusion was that a conceptual development of a suitable interface and application possibility between risk management and BIM is necessary under consideration of standardised data formats [20].

One way to connect risk management and BIM is to integrate the relevant information into an open data model. Not all BIM-related software can support the generation and management of risk information [21].

4. Requirements for the further development of IFC with regard to risk management

The results of the process analysis on risk management as well as the survey of existing degrees of realisation of risk management in practice show that a deeper standardisation as well as the inclusion of further information are necessary for a more effective implementation. Thererfore, this chapter presents recommendations for the further development of IFC with regard to risk management in a construction project.

4.1. Analysis of the consideration of risk management in IFC

Manufacturer-independent, lifecycle-oriented and internationally recognised exchange formats, in addition to processes, represent an essential basis for the successful application of the BIM method. The Industry Foundation Classes (IFC) offer such an international, manufacturer-neutral, lifecycle-spanning and open exchange format, which enables an open exchange between the project participants and the software systems used by the project participants [5] [15]. IFC are defined and developed by buildingSMART and updates and extensions are published at regular intervals. These are specified in ISO 16739, the current version is IFC4.3.dev [22]. This standardisation makes IFC suitable as an open standard for the exchange of information for the loss-free transfer of building data models [23]. The basis is the description of an object-oriented data model with its geometric and alphanumeric parameters and attributes. The contents of an IFC file are, for example, the project structure, model elements, CAD layers, model element specifications, relations between structural and model elements, quantity specifications, manufacturer specifications and material names [2]. For this purpose, the IFC format is divided into layers; elements from upper layers can refer to lower layers [24]. Specifications for objects and their attributes are made in the respective layers. In addition, property sets (PSets) are defined in IFC, which serve to group attributes in clusters (e.g. PSet_PumpTypeCommon for the definition of attributes for pumps or PSet_Warranty for the description of attributes for warranties) [25]. The relationship between an object and a PSet is established via the entity IfcRealDefinesByProperties [26] defined in IFC, which is shown in Fig. 4.

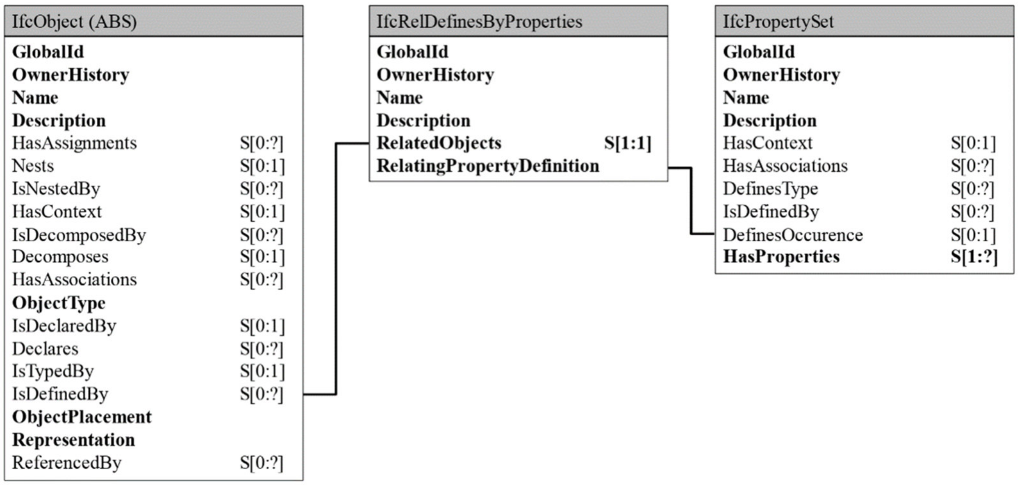

Figure 4. Relationship between an object and a PSet Source: own illustration in accordance with (buildingSMART 2019)

An analysis of the attributes in an IFC data structure with regard to the mapping of risk management shows that currently only the PSet_Risk contains attributes for risk management (see also section 4.2). The PSet_Risk is classified in the schema IfcSharedFacilitiesElements, which together with IfcProcessExtension and IfcSharedMgmtElements describes the basic concepts for facility management (FM) [27]. There is no further naming of entities or PSets with associated attributes for risk management, e.g. in the schema IfcConstructionMgmtDomain.

Initial research projects are investigating the integration of risk management, BIM and IFC (see for example [28] [29] [30]. However, these research projects also show that IFC does not yet fully enable the integration of risk management. For example, Zhou et al. describe that IFC does not have sufficient entities to fully represent the risks of the project, so that the IfcBuildingProxy entity is regularly used for integrating risk information in the objects [30]. However, this entity has strong restrictions as it does not describe a specific object [31] and information losses may occure.

4.2. Proposal for the further development of PSet_Risk

As described in Section 4.1, PSet_Risk offers initial approaches to implement this information linkage. In order to make full use of the advantages of the BIM method, it is important to map the risk information in its entirety using IFC. Only in this way can qualitative and quantitative assessments be carried out within the framework of the risk management process. The following is therefore an exemplary application of the PSet-Risk in a digital building model in order to compare the data of the PSet_Risk contained in IFC with the previously evaluated data relevant for the planning and construction process. The exemplary application was carried out in the digital building model of a new building of a public educational institution, which was commissioned in 2018. The digital building model, which is shown in Fig. 5, was modelled as part of an ongoing research project, continuously updated and is thus available to the authors for further research.

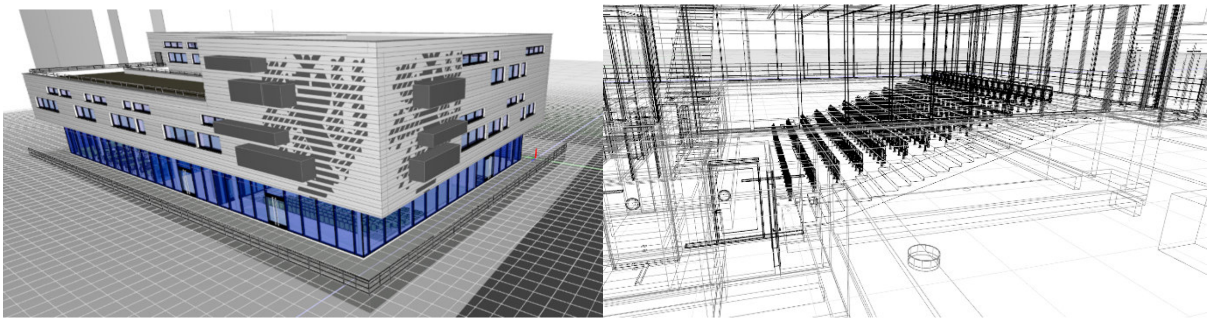

Figure 5. Screenshots of the digital building model Source: own illustration

Table 1 below summarises the results of this comparison. It indicates that seven attributes from the PSet_Risk are congruent with the attributes that were evaluated and described as relevant in the analyses and surveys presented in Chapter 3. For ten pieces of information that are relevant from a practical point of view, there are currently no attributes in the PSet_Risk, so that no open data transmission based on IFC is currently possible for this information. The attribute AuffectsSurroundings is defined in IFC, but has not yet been described as relevant in the analysis. A further evaluation can be carried out on this.

Table 1. Reconciliation of Pset_Risk with the risk management process informations

Step of the risk management process	Relevant information from the perspective of the surveyed practice partners	Attributs PSet_Risk
Identification	Numeration	RiskType
	Description of the risk	-
	Short name	-
	Risk cause	RiskCause, NatureOfRisk, SubNatureOfRisk1, SubNatureOfRisk2
	Risk impact	RiskConsequence
	Risk category	-
Assessment	Probability of occurrence	AssessmentOfRisk
	Impact costs	-
	Impact deadlines	-
	Impact quality	-
	Approx. Date of occurrence	-
	Risk priorisation	RiskRating
Control	Countermeasure Acceptance	-
	Countermeasure Transfer	-
	Countermeasure Avoidance	-
	Countermeasure Mitigation	PreventiveMeasures
	Risk owner	RiskOwner
Monitoring	Revision date	-
		AffectsSurroundings

Accordingly, it seems necessary to expand the attributes in PSet_Risk with additional attributes that can map the information necessary from a practical perspective. To ensure clarity, the existing PSet_Risk could be divided into four subsets, which are oriented towards the risk management process:

1. PSet_Risk_Identification for the identification of risks,
2. PSet_Risk_Evaluation for the evaluation of risks,
3. PSet_Risk_Steering for the control of countermeasures and
4. PSet_Risk_Monitoring for monitoring risk management.

When working with risk management, the four steps of the risk management process form a guideline and define the actions taken along process. Depending on the step that is being adressed within a project, different data will be used and connected to a model. To keep this logic of the risk management process we recommend using those four PSets. It will support the understanding of risk data within a model and provide the data in an easily adoptable way. The exchange and storage of risk management data can be supported and optimised by the further development of PSet_Risk. The IFC-based digital building model then offers the possibility for transparent and traceable, data-based processes in risk management. The additional amount of data due to the application of risk management to the models is manageable and is therefore to be treated neutrally.

5. Validation of further development

In order to validate the proposal mentioned in section 4.2, the results on the integration of risk management in BIM were continuously validated. For this purpose, workshop methods such as the 'World Café' method were used. The aim of this method is to bring workshop participants into an open discussion by assigning them to smaller and changing groups. This minimises the possible reticence of individuals to introduce topics in front of the whole group. Problems are discussed and reflected upon intensively within a given time frame. The final stage is the presentation of the individual groups to all participants. In addition, the participants were asked in expert interviews about their current status in the application of risk management in their company [8].

The aforementioned workshop took place in March 2021 as part of a practice partner meeting of the research project 'BIM-based risk management'. Each practice partner was led into a predefined zoom session with another practice partner. The small groups answered three predefined questions about the digital building model and its implementation. These were critically examined and answered in the allotted time of ten minutes. The questions were:

- How do you rate the practicality?
- What templates do you need for your chosen software or exchange format to support the application of your risk management process?
- How do you rate the current application possibilities of risk management in software solutions/exchange formats?

The answers were shared by each practice partner after the zoom sessions and discussed with the participants present. 14 practice partners took part in the workshop. Six practice partners have a managerial position in construction companies. Eight practice partners gave their input from the perspective of building owners and project managers. The workshop was conducted by a research team from the University of Wuppertal. On the question of the practical suitability of the model, all participants gave positive to very positive feedback on the added value of practical application. On the question of the information required, there was feedback that the available attributes cannot fully represent the risk management process of a construction project and that the focus here is only on technical risks. In conclusion, all participants of the workshop agreed that there is high potential in the application of risk management through the IFC exchange format, but that a detailing of the application specifications is necessary. The participants stated that the integration of risk information into the digital building model has a high added value for communication between the project participants and that the information can be used for the transfer of knowledge into the company and for the documentation of the construction project. According to the participants, there is a lack of mature standardisation and mapping in open data exchange formats.

6. Conclusion and perspectives

This paper demonstrates that BIM-based linking of risk management information with the digital building model is possible. The findings revealed a need for linking risk information with an IFC file. The presented approach is one solution. In addition, further research should be conducted in order to confirm, for example, optimisations in the planning, execution and operation of buildings. This is due in particular to a structured growth of information over the project cycle, the as-is state of a building that can be retrieved at any time, and the digital traceability of changes.

These optimisation potentials can be generated in particular when open exchange formats such as IFC are used within the framework of the BIM method. However, the analysis and surveys carried out show that the attributes currently contained in IFC are not sufficient to fully map the risk management process. In particular, essential attributes are missing in PSet_Risk, thus no qualitative and quantitative assessment of the risks as well as no differentiation in the extent of damage between costs, deadlines and quality are possible. Furthermore, the roles in the risk management process are not fully mapped.

This is where the proposal for the further development of PSet_Risk can be applied. Through the further development, attributes are integrated that enable a qualitative and quantitative assessment of the risks and can also map the risk management processes in IFC. This will allow the information relevant to risk management to be stored, exchanged and evaluated over the entire life cycle on the basis of open exchange formats. Continuing risk management in all life cycle stages is crucially important to fully use the potential of risk management. IFC simultaneously enables the integration of risk information from all stakeholders and the use of the information by these stakeholders. Since it is particularly important for the success of risk management to involve all stakeholders, this approach is of outstanding importance.

This article presents the first results of a research project at the University of Wuppertal. Based on the available analysis and results, further research will be conducted to further improve the integration between BIM, open exchange formats such as IFC and risk management.

References

[1] BMVI 2021 *Digitales Planen und Bauen Stufenplan zur Einführung von Building Information Modeling (BIM)* [Online] Available at: https://www.bmvi.de/DE/Themen/Digitales/Building-Information-Modeling/building-information-modeling.html

[2] Egger M and Hausknecht K and Liebich T and Przybylo J 2021 *BIM-Leitfaden für Deutschland: Information und Ratgeber* Endbericht [Online] Available at: https://www.bmvi.de/SharedDocs/DE/Anlage/DG/Digitales/bim-leitfaden-deu.html

[3] Borrmann A and König M and Koch C and Beetz J 2015 *Building Information Modeling: Technologische Grundlagen und industrielle Praxis* (Wiesbaden: Springer Vieweg)

[4] Industry Foundation Classes (IFC) 2020 *für den Datenaustausch in der Bauwirtschaft und im Anlagenmanagement: Teil 1: Datenschema*, DIN EN ISO 16739-1 (Berlin: DIN EN ISO)

[5] Bartels N 2020 *Strukturmodell zum Datenaustausch im Facility Management*, 1. Aufl. (Wiesbaden: Springer Vieweg).

[6] Boduch A 2017 *Learning jQuery 3 - Fifth Edition* (Packt Publishing)

[7] Welge M K and Al-Laham A 2007 *Strategisches Management*, 5. Aufl. (Wiesbaden: Gabler)

[8] Brown J and Isaacs D 2008 *The World Cafe: Shaping Our Futures through Conversations That Matter* (San Francisco: Berrett-Koehler Publisher inc.)

[9] Lehr- und Forschungsgebiet Baubetrieb und Bauwirtschaft 2017 *Teil 1: Grundlagenbericht - Building Information Modeling und Prozesse* (Wuppertal)

[10] Li Y T 2015 *BIM-Risk System for Chinese International Contractors* AMM, pp 181–186 doi: 10.4028/www.scientific.net/AMM.719-720.181.

[11] Zou Y and Kiviniemi A and Jones S W 2015 *BIM-based Risk Management: Challenges and Opportunities* CIB W78 Conference 2015, 27th-29th October 2015 (Eindhoven: The Netherland)
[12] Zhang L and Wu X and Ding l and Skibniewski M J and Lu Y 2016 *BIM-Based Risk Identification System in Tunnel Construction* Journal Of Civil Engineering And Management, Jg. 22, No. 4, pp 529–539 doi: 10.3846/13923730.2015.1023348.
[13] Normenausschuss Sicherheitstechnische Grundsätze im DIN 2009 *Risikomanagement - Grundsätze und Leitlinien (ISO 31000:2009)*
[14] Diederichs M 2012 *Risikomanagement und Risikocontrolling*, 3. Aufl. (München: Franz Vahlen)
[15] Borrmann A and König M and Koch C and Beetz J 2018 *Building Information Modeling: Technology Foundations and Industry Practice* (Switzerland: Springer)
[16] Sartor F J 2013 R*isikomanagement Kompakt: In 7 Schritten zum aggregierten Nettorisiko des Unternehmens* (Berlin/Boston: Walter de Gruyter GmbH)
[17] Eilers M and Pütz C and Helmus M and Meins-Becker A 2020 *Wenn fehlendes Risikomanagement zum Risiko wird*, Build-Ing., August 2020 [Online]: https://www.build-ing.de/fachartikel/detail/wenn-fehlendes-risikomanagement-zum-risiko-wird/
[18] DIN ISO 31000 *Risikomanagement - Leitlinien (ISO 31000:2018)* DIN Deutsches Institut für Normung e.V., DIN ISO 31000:2018-10, Berlin, Okt. 2018.
[19] Hoffmann W 2017 *Risikomanagement* 2. Aufl. (Berlin, Heidelberg: Springer Berlin Heidelberg)
[20] Helmus M and Eilers M and Pütz C and Meins-Becker A 2022 *Maßnahmen zur Umsetzung eines effizienten Projektrisikomanagements durch Einsatz der Methode BIM: BIM-basiertes Risikomanagement* Endbericht Forschungsprojekt der Lehr- und Forschungsgebiete Baubetrieb und Bauwirtschaft, Bundesinstituts für Bau-, Stadt- und Raumforschung (BBSR) im Bundesamt für Bauwesen und Raumordnung (BBR), Wuppertal
[21] Zou Y and Kiviniemi A and Jones S W and Walsh J 2019 *Risk Information Management for Bridges by Integrating Risk Breakdown Structure into 3D/4D BIM* KSCE J Civ Eng, Jg. 23, No. 2, pp 467–480, doi: 10.1007/s12205-018-1924-3.
[22] buildingSMART *IFC Specifications Database* [Online] https://technical.buildingsmart.org/standards/ifc/ifc-schema-specifications/
[23] Zeitner R and Peyinghaus M 2015 *IT-Management Real Estate: Lösungen für digitale Kernkompetenzen* (Berlin: Springer Vieweg)
[24] Treeck v T and Elixmann R and Rudat K and Hiller S and Herkel S and Berger M 2016 *Gebäude.Technik.Digital: Building Information Modeling* 1. Aufl. (Berlin, Heidelberg: Springer Berlin Heidelberg)
[25] buildingSMART *Industry Foundation Classes: Version 4* Addendum 2. [Online] https://standards.buildingsmart.org/IFC/RELEASE/IFC4/ADD2/HTML/
[26] buildingSMART *IfcRelDefinesByProperties: lexical* [Online] https://standards.buildingsmart.org/IFC/DEV/IFC4_3/RC2/HTML/schema/ifckernel/lexical/ifcreldefinesbyproperties.htm
[27] buildingSMART *IfcSharedFacilitiesElements* [Online] https://standards.buildingsmart.org/IFC/RELEASE/IFC4/ADD2/HTML/schema/ifcsharedfacilitieselements/content.htm
[28] Zou Y and Kiviniemi A and Jones S W 2017 *A review of risk management through BIM and BIM-related technologies* Safety Science, Jg. 97, pp 88–98, doi: 10.1016/j.ssci.2015.12.027.
[29] Zhang S and Teizer J and Lee J-K and Eastman C M and Venugopal M 2013 *Building Information Modeling (BIM) and Safety: Automatic Safety Checking of Construction Models and Schedules* Automation in Construction, Jg. 29, pp 183–195, doi: 10.1016/j.autcon.2012.05.006.
[30] Zhou Y and Hu Z-Z and Zhang W-Z 2018 *Development and Application of an Industry Foundation Classes-Based Metro Protection Information Model* Mathematical Problems in Engineering, Jg. 2018, pp 1–20, doi: 10.1155/2018/1820631.
[31] buildingSMART *IfcBuildingElementProxy* [Online] https://standards.buildingsmart.org/IFC/RELEASE/IFC2x3/TC1/HTML/ifcproductextension/lexical/ifcbuildingelementproxy.htm