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Indoor Geography in the Production Environment

How Location and Time can support Smart Manufacturing

DOCTORAL THESIS

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Abstract

Productivity, efficiency and quality are the key to success for manufacturers, especially if they have a highly flexible and dynamic indoor production line environment which is not sequentially aligned. Therefore, transportation processes and indoor environmental monitoring are of high interest for automation, optimization and quality assurance.
The motivation for this research lies on the novelty of applying Geographic Information Science and Technology (GIS&T) in an indoor industrial environment. Therefore, there is the potential to increase productivity and to support data forensics. Additionally is the analysis of parallels between outdoor and indoor applications for the reusability of methods and tools.
The goal of this doctoral thesis is to apply GIS&T in an indoor production environment by supporting transportation processes paired with spatial suitability over space and time. The research question can be summarized as 'How can GIS&T help to optimize transportation processes in a complex and highly flexible indoor production environment by increasing productivity and ensuring product quality'?. This research question includes the needed data structures, semantics and changes of algorithms. In a first step, the conceptualization of the indoor production environment and indoor tasks is modelled to generate shared knowledge for re-usability. In the second step, the conceptualized data model is adjusted with typed links enabling data semantics and also to link heterogeneous data sources to a Linked Manufacturing Data approach in a spatial graph database. In a third step, this Linked Manufacturing Data approach is then utilized for a successful navigation based on affordances, whereas the concept of affordances also includes spatial suitability of the indoor production environment based on sensors. In fact, the navigation based on affordances adds quality concerns to the transportation processes. Further, spatio-temporal pattern recognition is applied by covering the semantically annotated manufacturing data. The space and time capability connected with data semantics enables the analysis of data similarities.
The results of this research show the applicability of Geographic Information Science and Technologies in a production environment. On one hand, the result includes a spatial graph database representing semantically annotated manufacturing data as Linked Manufacturing Data based on a beforehand

implemented indoor navigation ontology with typed data links. On the other hand, is the applied Linked Manufacturing Data approach on the navigation based on affordances which adds spatial suitability to transport optimization and spatio-temporal pattern recognition based on similarities. This is helpful as an optimized and more accurate manual transport increases productivity and efficiency. Furthermore, via linking affordances to navigation and the execution of spatio-temporal analysis, it is possible to increase quality assurance which is getting an increased importance for customers.

Zusammenfassung

Die Wettbewerbsfähigkeit für Produktionsfirmen ist sehr stark abhängig von der Produktivität, Effizienz und der Qualität der erzeugten Produkte. Erschwerend ist dies für Produktionsfirmen mit einer nicht sequentiell aufgebauten Produktionslinie und einem flexiblen und dynamischen Produktionsumfeld. Aus diesem Grund sind Transportprozesse und Monitoring der Indoor-Umgebung von großem Interesse für Automatisierung, Optimierung und Qualitätssicherung in der Produktionslinie.

Die Neuheit und Motivation für diese Forschungsarbeit liegt in der Anwendung von Geoinformation innerhalb einer Industrieumgebung, einer Produktionshalle. Mit Methoden der Geoinformation wird das Potential für Produktivitätssteigerung und Qualitätsanalysen untersucht. Des Weiteren werden Parallelen zwischen Geoinformationsanwendungen im Innenraum und in der Außenwelt analysiert.

Das Ziel dieser Doktorarbeit ist die Evaluierung von Geoinformationstechnologien um eine zeitlich-räumliche Entscheidungsunterstützung anzubieten. Die Idee ist die Unterstützung von Transportprozessen und der räumlichen Eignung um einen 'intelligenten' Transport anzubieten. Im ersten Schritt ist ein konzeptionelles Modell des Indoor-Produktionsumfeldes und der Transportprozesse. Im zweiten Schritt wird das entwickelte konzeptionelle Model mit einem 'Linked Data'-Ansatz realisiert. Dieser Ansatz wird in einer räumlichen Graph Datenbank umgesetzt und mit manuellen Datenlinks erweitert, um heterogene Datenquellen zu verbinden. Der Linked Data Ansatz wird für eine Navigation basierend auf Angebotscharakteristiken verwendet, um den optimalen Transportweg für Produktionsgüter zu finden. In diesem Fall beinhalten die Angebotscharakteristiken auch die räumlichen Gegebenheiten des Produktionsumfeldes basierend auf Sensorüberwachungen. Durch diese Art der Navigation werden Qualitätskriterien bei Transportprozessen berücksichtigt. Zeitlich-räumliche Analysen werden umgesetzt und beinhalten semantisch angereicherte Produktionsdaten durch den verwendeten Linked Data Ansatz. Die potenziale von Zeit und Raum verbunden mit Semantik ermöglichen die Analyse von Ähnlichkeiten.

Die Resultate von dieser Forschungsarbeit beinhalten die Umsetzung von Geoinformationstechnologien in einem Produktionsumfeld. Eine räumliche Graph Datenbank repräsentiert semantisch angereicherte Produktionsdaten

in einem Linked Data Ansatz. Dieser Ansatz basiert auf einer ‘Indoor Navigation Ontology‘ mit adaptieren Datenlinks. Navigation basierend auf der Anforderungscharakteristik von Produktionsgütern ist umgesetzt und verknüpft Transportoptimierung mit räumlichen Gegebenheiten. Zeitlich-räumlich Analysen ermöglichen die Verknüpfung von Ähnlichkeiten basierend auf Datenlinks. Diese Resultate sind hilfreich, weil dadurch der manuelle Transport von Produkten präziser wird und die Qualität der Produkte ein immer wichtiger werdender Bestandeil ist.

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Contents

List of Abbreviations

GIS&T	Geographic Information Science and Technology
IoT	Internet of Things
LD	Linked Data
LMD	Linked Manufacturing Data
OGC	Open Geospatial Consortium
OWL	Web Ontology Language
RFID	Radio Frequency Identification
RDF	Resource Description Framework
SDI	Spatial Data Infrastructure
SOMs	Self-Organizing Maps
UoD	Universe of Discourse
URI	Uniform Resource Identifier
WIP	Work in process
W3C	World Wide Web Consortium
XML	Extensible Markup Language

Chapter 1

Introduction

The fundamental issue of this doctoral thesis is the investigation of a novel approach utilizing Geographic Information Science and Technology (GIS&T) to support smart manufacturing. Therefore, the focus is on applying GIS&T in a highly flexible and dynamic indoor production line environment of a semiconductor manufacturer. The indoor environment under review provides special requirements, which have to be considered within the application of GIS&T indoor. These requirements set up the basis for quality assurance in a cleanroom and the analysis and optimization of indoor navigation tasks for transportation processes. Therefore, the research starts with an extensive literature review about GIS&T indoors leading to a formal description of the indoor environment including conditions and the navigation tasks as an ontology. This formal description of the indoor environment at hand is annotated with typed links. The established typed links enhance data semantics leading to a Linked Manufacturing Data (LMD) approach represented as spatial graph database. Further topics comprise affordance-based navigation and the identification of space and time patterns. Navigation based on affordances is implemented to identify the optimal navigation path based on the LMD approach. The analysis of space and time is based on spatial and temporal enhanced LMD and covers also data semantics to identify production asset similarities. Additionally, the research refers to the analysis of parallels between outdoor and indoor tasks.
This introduction chapter covers the main motivation for the carried out research from the science and the industry perspective. Further, a brief delineation of the research problems and the project goals is stated. Then, a short methodology is presented outlining the scientific approach. The expected results are summarized followed by the intended audience of the research. In the end, the general structure of the thesis is described.

1.1 Universe of Discourse :: Dynamic Indoor Production Environment

The Universe of Discourse (UoD) represents a highly flexible and dynamic production line environment of a semiconductor manufacturer, which does not follow the typical conveyor belt metaphor. The production line environment itself is a cleanroom environment with special air conditions and thus, the physical space is rare as it is cost intensive. To clarify, the production halls are located on different building levels incorporating also a vertical transportation, cleanroom restrictions and the production assets. The production assets are of main interest, as they are transported throughout the UoD. The movement or the transportation is also multi-faceted in the expensive indoor environment, where the production assets move up to several kilometres in a complex process chain. Therefore, the movement is tracked by an existing indoor positioning solution (Thiesse et al., 2006). Main characteristics of the UoD and the production asset can be summarized as:

- Production steps are executable on several equipment in the production line environment, which are also spatially dispersed over the indoor environment and they can also be located in different building levels.

- A high number of different types of production assets are present at the same time in the indoor production environment. Each production asset has to fulfil several hundred production steps including different degrees of completion.

- The overall processing time varies based on the priority and the type of asset. Therefore, also production artefacts vary from several days up to a few weeks.

- The processing time and the production quality for a production step depend also on the equipment.

To get an impression of the UoD, figure 1.1 illustrates a topological model of the indoor production environment. Figure 1.1 includes a blank space to disguise the complete layout and standardized yellow polygons are used to represent the equipment. The existing indoor positioning system is visualized in light gray covering the complete production halls. Production assets are included as black boxes. The movement of one single box is visualized based on a gray box and includes the movement visualized as blue arcs, which refers to the timestamping of the indoor positioning solution.

Figure 1.1: *Topological model of the indoor production environment including layout, equipment (yellow), production asset (boxes), movement (arcs) and the indoor positioning system.*

1.2 Motivation from a Business Perspective :: Industry 4.0

Manufacturing is a highly competitive field. To compete, manufacturers are more and more digitizing their operation processes and there value chains (pwc, 2016). This digitalization leads to smart manufacturing or Industry 4.0. Additionally, emerging automation in manufacturing is present to enhance competitiveness for productivity and efficiency as key to success (Davis et al., 2012). Thus, transportation processes, quality monitoring and allocation of processes can be addressed with GIS&T (Nyström et al., 2006), which supports the ability of humans to analyse visual patterns easily (Compieta et al., 2007). Therefore, literature provides approaches to increase efficiency of manufacturing lines (Davis et al., 2012; Nyström et al., 2006; Scholl and Becker, 2006). The focus of manufacturers is on the competitiveness, especially as global markets are more and more competitive. Thus, there is the need for strategies to increase productivity, efficiency and to realize cost savings. Therefore, figure 1.2 presents a survey about expected investments, revenues and reduced costs (pwc, 2016). This statistic shows, that there is a massive amount of investments which have to be made to be fit for the digitization to gain a higher revenue and also to reduce costs. This shows, that smart manufacturing or Industry 4.0 clearly brings enormous benefits but getting there will not be easy and it is not cheap (pwc, 2016). However, it is changing current industry and manufacturers.

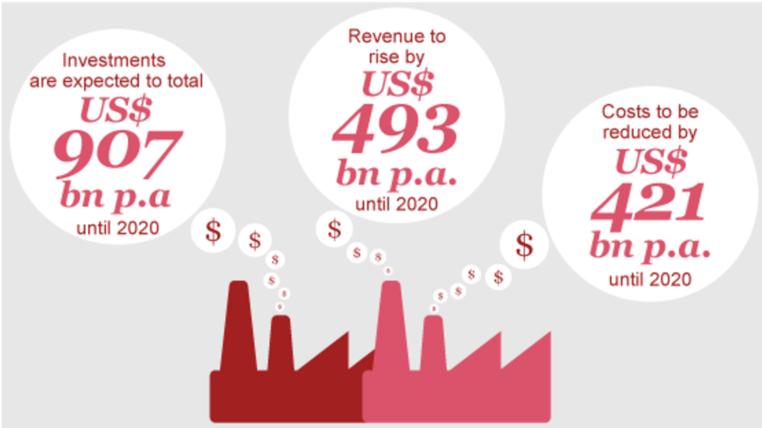


Figure 1.2: *Overview of the need for digitization to compete in Industry 4.0 showing the amount of expected investments, revenue and costs (pwc, 2016).*

According to Hermann et al. (2016), the digitization in manufacturing includes cyber-physical systems, the internet of things and cloud computing. Therefore, also wearable devices for managers and employees can be utilized (Osswald et al., 2013). A framework for the term Industry 4.0 is defined by pwc (2016), highlighting digital technologies having an impact on the digitization. Figure 1.3 separates digital technologies into the integration of the horizontal or vertical value chains, digital business and the digitalization of the production and service offerings. Therefore, the basis is on data analytics, which is based on a variety of digital techniques such as mobile devices, smart sensors, wearables and many more which can be see in figure 1.3 (pwc, 2016).

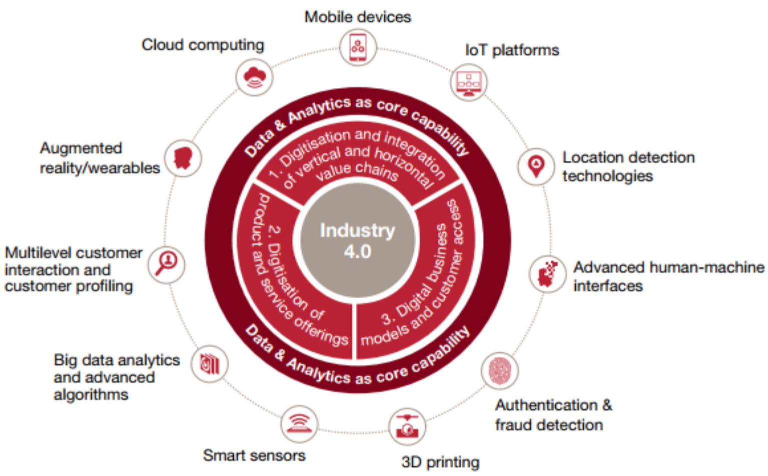


Figure 1.3: *Technologies contributing to Industry 4.0 (pwc, 2016).*

Key findings of a survey on Industry 4.0 by pwc (2016) are illustrated in figure 1.4. They start with a deepened digital relationship between manufacturer and customer, include peoples culture, big data analytics, globalization, big investments and ends with actions of manufacturers (pwc, 2016).

Figure 1.4: *Key findings of digitalization leading to Industry 4.0 (pwc, 2016).*

1.3 Motivation of Science :: Geographic Information Science and Technologies indoor

Currently, the trend of GIS&T goes from outdoor to indoor, which opens new research areas and is reasonable as an average person spends about 90% inside (Worboys, 2011; Giudice et al., 2010). Additionally, the trend is paired with the development of indoor positioning solutions and indoor navigation assistance (Afyouni et al., 2010). Therefore, outdoor applications of GIS&T have to be prepared for indoor. Based on this, there is the motivation to apply a novel approach of GIS&T in a highly flexible indoor production environment.
To deal with the outdoor to indoor trend of GIS&T, indoor spatial modelling is essentially. Therefore, the motivation for indoor spatial modelling is the capability of combining building complexity, functionality and accessibility.

Thus, indoor spatial modelling is not a straight forward task (Meijers et al., 2005). The importance of indoor spatial modelling is assured by Li (2008), Isikdag et al. (2013) and Zlatanova et al. (2014).
The application of GIS&T in an indoor production environment aims to show the potential for manufacturing optimization, which is of high interest for industry outlined in section 1.2. Therefore, GIS&T is used to show the potential to optimize transportation processes by combining transportation and quality assurance. The transportation optimization includes affordances and spatial suitability into wayfinding processes, which is possible as production entities have to satisfy certain needs and constraints. Additional motivation is based on the dimensions space and time, to analyse historic data of movement and measurements to monitor potential bottlenecks or to show the potential of incident management. This is possible, as manufacturing data is strongly intertwined with space and time referring to movement, production processes, quality measurements and environmental influences.
Further motivation lies on the connection and integration of heterogeneous datasets-/systems-/applications present in a production environment. Based on a successful connection of distributed data sources, there is the overall possibility to gain new knowledge and to show the potential how location and time can support smart manufacturing. This motivates to utilize a Linked Data (LD) approach to support the integration of data sources (Schmachtenberg et al., 2014). In fact, motivating is also the advantage of the included enhancement and enrichment of semantic annotations and spatial information based on new data links. By omitting interoperability issues of heterogeneous sources and establishing semantically enhanced spatial data, new knowledge is possible for map generation and visual analysis.
In order to close the gap between outdoor and indoor, the carried out research analyses parallels between outdoor and indoor at a task-level. Therefore, a task can be analysed outdoor and indoor with the same general task (i.e.: transportation task), but with a different context (i.e.: manufacturing or parcel delivery). The context-awareness is considered via data modelling and the refinement of a task into atomic sub-tasks to solve a complex problem. Thus, re-usability is supported as similar sub-tasks which do not have to be changed for tools and applications.
To summarize, the main motivation refers to the application of a novel GIS&T approach in a complex indoor production environment. This novel application considers indoor spatial modelling, linked data, navigation, spatio-temporal data analysis and the investigation of outdoor and indoor parallels.

1.4 Research Interests & Project Goals

The main research interest of this doctoral thesis is the application of GIS&T in a highly flexible indoor production line environment of a semiconductor manufacturer. Through this manufacturing context inside a production environment and the paradigm shift of bringing GIS&T from outdoor to indoor, the research presents a novel approach. A complex indoor environment is the basis for spatial indoor modelling, including the modelling of indoor wayfinding for transportation of production assets. Therefore, the modelling includes the environment, the task and affordances describing what the environment and the production asset offer for transportation. The indoor model is then used for a semantic annotation of data as LMD enabling new analysis capabilities such as a similarity analysis of production assets. Parallels between outdoor and indoor are analysed at a task-level comprising a smart transportation task. This smart transportation task is then implemented as navigation based on affordances. Spatio-temporal data analysis is used to identify potential bottlenecks and the investigation of similar assets to speed up processes.
The scope of this research in the context of GIS&T applied in a flexible indoor environment of production line covers:

- Indoor Spatial Modelling is of main interest to get a clear understanding of the building structure, the field of application and the building complexity. The indoor spatial model is combined with a 2D visualization, which is seen more effective than a 3D visualization. It establishes a clear view on the context of the UoD and process characteristics (see section 1.1), which are modelled as affordances. The affordances describe what the environment offers based on the logical consistency of the modelling and reasoning.

- Manufacturing processes address in general transportation and processing. The processes are sophisticated, as at the same time there is a high number of assets and processes which have to be carried out with different degrees of completion and types of assets described in section 1.1. Additionally, transportation processes are monitored via a Radio Frequency Identification (RFID) and Ultrasound based positioning system (Thiesse et al., 2006).

- A challenge is to overcome interoperability issues, which are a result of distributed heterogeneous data sources and systems in the UoD. To solve these interoperability problems, a LD approach is suggested with the capabilities of data integration of different sources (Schmachtenberg et al., 2014) addressed as LMD. However, LD is also a shift in GIS&T and offers new ways off structuring, publishing, discovering, accessing and integrating data (Kuhn et al., 2014). The needed data structure enhances manufacturing data also with relationships and semantics.

- By bringing GIS&T indoor, the connection to outdoor is also a main concern for re-usability of applications and technology. Thus, there is the analysis of mapping parallels between an indoor transportation task and an outdoor transportation task. Therefore, a task decomposition is applied on a smart transportation task, dividing the complex overall task into sub-tasks until they are atomic tasks and can individually be solved. Via this method, sub-tasks can be solved based on affordances and compared leading to the general result of the task. The smart transportation task covers navigation based on affordances. The comparison of parallels is important, as it shows a potential method how outdoor applications can be re-used indoor.

- Navigation based on Affordances is implemented based on the LMD approach in the production environment for smart transportation. Thus, the goal is to determine the optimal path based on affordances which show what the entities offer to the transported objects and the spatial suitability which can be weighted (Jonietz and Timpf, 2013). The navigation based on affordances has to include affordances, context, spatial suitability and asset or equipment affordances. So basically, navigation based on affordances has to consider what the environment, the asset or the equipment offer to the navigation task. This includes questions such as 'what is the next equipment' and if multiple equipment are possible 'which one is the most suitable'. In example, a stair and an elevator afford both the traversal of an asset, but the elevator is much more suitable which sets the evidence on the weighting of affordances. Additionally, this approach supports the optimal transportation of an asset in respect to quality.

- Spatio-temporal data analysis is important for the analysis of potential bottlenecks and in general to support humans with geo-visual analytics (Compieta et al., 2007). Map generation aims to support the human to analyse huge amounts of manufacturing data. Manufacturing data is analysed based on the linked manufacturing data, which potentially gains new insights over space, time and similarities of semantically enriched data. This connection between space, time and similarities could support smart manufacturing in terms of quality assessment via an innovative linking and analysis of data. Spatio-temporal analysis is applied in two different ways. On one hand, on a separate heterogeneous data system to show how GIS&T can be applied on movement data and transportation data. Therefore, a cluster-method is implemented to analyse the movement behaviour based on stored historic production asset movements. On the other hand, the spatio-temporal data analysis is enhanced with the LMD approach, adding new capabilities such as the analysis of similarities based on data semantics. The analysis of similarities is utilized by adding value on the identification of similar production assets based on defined data links. In case of the identification of an affected asset, potential assets are identified beforehand based on space, time and similarities to ensure quality and speed up incident identification.

- The evaluation of the results is necessary to prove the developed concept and to validate the correctness of navigation optimization and spatio-temporal data analysis. The validation is challenging as it includes new knowledge of existing and linked data sources. In general, evaluation is crucial as a high value is paired with decisions and therefore the research is a demonstrator for industry to show new possibilities.

Not covered within this thesis is the set up of the indoor positioning solution nor the evaluation of position accuracy of the existing RFID and Ultrasound positioning solution (Thiesse et al., 2006). Also not scope of this research is the development of a finalized decision tool, as the aim is to show how GIS&T is applied in an indoor production environment, demonstrators are implemented to show the potential of GIS&T applied indoors.

1.5 Methodology

The proposed method of solution starts with an exhaustive literature review to gain insights into the topics of interest, especially the paradigm shift from applying GIS&T indoor. The method of solution aims to show a potential combination of GIS&T indoor and smart manufacturing - Industry 4.0. The literature review of the spatio-temporal data compared to the manufacturing data and the UoD results in a formal data description. Further, the literature review shows how the topics of interest can be combined leading to the result of the application of GIS&T in a complex indoor production environment.

The gained knowledge of the literature review results in a formal data description of the UoD and manufacturing data. The formal data description is implemented in an application ontology including the context of the indoor environment and the navigation task. The formal data model is extended with new relationships and typed links, which are used to connect data and also to describe affordances. Thus, the application ontology also comprises affordances, which describe what the environment offers. The affordances are derived from the review of manufacturing data and the UoD. The application ontlogy is filled with manufacturing data and reasoning is executed to check the logical consistency of implemented relationships and data links. The ontology is then transformed in the Resource Description Framework (RDF) data triple format (Subject, Predicate and Object). This transformation into RDF is the first step towards a LD approach, in this research coined as LMD.

To implement this LMD approach, a graph-database is implemented based on the formal data description of the ontology. This LMD approach enhances data with semantics. Further manufacturing data are added and therefore typed links and relationships are established with enhanced semantics. Due to the fact of the spatial capability of the implemented graph database, the spatial component adds a variety of spatial analysis capabilities. In addition to spatial queries also spatial links are possible to establish new data links. This LMD approach is the basis for the further research and indoor application of GIS&T, which refers to spatio-temporal data analysis, affordance-based navigation, and the analysis of outdoor and indoor parallels.

The spatio-temporal data analysis includes the analysis with Self-Organizing Maps (SOMs) of a heterogeneous data source and the analysis of space and time patterns with a similarity analysis of the LMD approach. Spatio-temporal data analysis refers to the identification of potential bottlenecks via map generation and cluster methods to identify visual patterns. Generally, space and time also support quality monitoring and incident identification by identifying potential affected production assets, linked with a similarity analysis of data semantics.

Navigation based on affordances is implemented to support optimal path for transportation processes in an indoor production environment. The optimal path combines indoor wayfinding and quality concerns in an indoor environment, addressed as smart transportation. This navigation approach includes the indoor environment, a graph-based network and the production asset and corresponding affordances defined by the formal data description. Therefore, the calculation is based on the LMD approach. The calculation generates an ad-hoc spatial suitability network which considers walkable ways affording the need for transportation and spatial suitability. The calculation follows the task decomposition of the smart transportation task, by solving small sub-tasks, i.E.: which equipment are possible to process the next process and which one is the most suitable one. The result of this implementation delivers the optimal path in terms of quality and spatial suitability.

The analysis of outdoor and indoor parallels is done via a comparison of a task carried out outdoor and indoor. Therefore, the smart transportation task is considered which includes affordances, context and the environment. The analysis is solved via a task decomposition, dividing a general task into atomic sub-tasks. Each of these atomic sub-tasks can individually be solved and the results can be concatenated to solve the general task. Through this task decomposition a task gets computational manageable and solvable via

affordances. However, the task-decomposition is also the basis for analysing outdoor and indoor parallels of a task.
To summarize, the literature on GIS&T applied indoors and manufacturing leads to a formal description of the UoD, which is the basis for the implemented LMD approach. The LMD approach is then utilized for the further research resulting in the analysis of outdoor and indoor parallels of a smart transportation task, the implementation of a smart transportation as navigation based on affordances and the analysis of spatio-temporal patterns.

1.6 Expected Results

The result of this research is the demonstration of GIS&T applied in a highly flexible production line and brings GIS&T from outdoor to indoor. Therefore, the demonstration covers indoor transportation, spatio-temporal data analysis and the analysis of outdoor and indoor parallels in respect to GIS&T. To achieve this demonstration, contemporary results are the modelled indoor environment as an ontology and semantically annotated manufacturing data as LMD. The intermediate results are as follows:

Indoor Navigation Ontology
The indoor navigation ontology represents the flexible and dynamic indoor environment of a semiconductor manufacturer including the transportation process and manufacturing data. This conceptualization covers re-usability, shared knowledge, relationships, typed links and reasoning. Furthermore, the developed application ontology supports the proof of logical consistency and the concept of affordances.

Linked Manufacturing Data
The LMD approach is the implementation of a spatial graph database. The spatial graph database is based on the beforehand developed indoor navigation ontology and utilizes semantic manufacturing data annotations proved by typed links and relationships. This spatial graph database supports the combination of heterogeneous data sources and thus enables new data links.

Navigation-Based on Affordances in a dynamic Indoor Manufacturing Environment
Affordance-based Navigation supports the identification of the optimal path. The optimal path is the result of the combination of spatial suitability and affordances of the production asset and the context. For the optimal path, the affordances describe what the indoor production environment offer the production asset for transportation. This optimal path is based on the LMD approach and supports quality assurance and monitoring.

Spatio-Temporal Data Analysis

Spatio-Temporal Data Analysis includes the analysis of manufacturing data, either based on the LMD approach or on a heterogeneous data source. The analysis of spatio-temporal patterns based on the LMD approach shows the combination of spatio-temporal data analysis including the similarity analysis.

Analysis of Parallels in Indoor and Outdoor Transportation Tasks

A transportation task is analysed to identify parallels of the same task outdoor and indoor. Task-decomposition is applied on the transportation task to find parallels and to solve the task including affordances. This ensures re-usability of applications and technologies.

Therefore, the research deals with GIS&T indoors and smart manufacturing. Generally, manufacturing data is strongly intertwined with space and time, which is considered in the formal data description as an ontology. This ontology provides the ability of implementing semantic data annotation and linked data. The formal data representation leads to a data architecture as graph database including semantics. The results are included as publications, whereas each publication covers one or two of the expected result topics. The approach itself, shows the applicability of GIS&T in an indoor production environment with respect to quality assurance and transportation of production assets. In addition, a discussion is provided evaluating the overall approach which aims to increase effectiveness, quality assessment and cost efficiency in production line processes.

1.7 Audience

The carried out research primarily addresses industries with a dynamic and highly flexible production line environment such as semiconductor manufacturer. There, high quality concerns refer to the indoor cleanroom and the production not aligned on a classical conveyor belt metaphor. Therefore, productivity and competitiveness is based on human operators with a potential for optimization and quality assurance by indoor environmental monitoring. The audience also includes manufacturers which try to automate tasks and sub-tasks to speed up processes and to make them less error prone. This supports the hypothesis, that there is the potential for improvement via spatial modelling and a spatial decision support in near real-time for future research activities.

Other interest groups focus also on the general research of GIS&T indoor, as till now the focus of GIS&T was outdoor. Thus, the proposed research can be beneficial for applying outdoor models or methods indoors and vice-versa. Additionally, GIS&T applied indoors is combined with research topics concerning spatial data modelling, linked data and navigation based on affordances including spatial suitability and context.

1.8 Structure of the Thesis

The second chapter outlines the theoretical background. This includes terms and definitions of outdoor, indoor, geography, smart manufacturing and manufacturing data. Further is formal data modelling comprising indoor spatial modelling, data representations and manufacturing data.
The scientific approach is stated in the third chapter. This chapter includes the general work-flow of related topics and their link to solve the stated research question. The main tasks include an indoor navigation ontology, a linked manufacturing data approach, navigation based on affordances, spatio-temporal patterns of manufacturing processes and the analysis of parallels between outdoor and indoor. Thus, the scientific approach presents the doctoral thesis as a cumulative publication dissertation referring to the topics of interest and how the publications are related.
Chapter four to eleven highlight the publications and papers of this research. Each of these chapters includes a short introduction about the publication, the link to the overall research about GIS&T applied in an indoor production environment and a description of the activities of each author.
Chapter twelve states summarizes the result and provides a conclusion and the research, which is a proof of the used concept. In addition, there is a discussion of the results and some future perspectives.

Chapter 2

State of the Art and Relevant Literature

This chapter reflects relevant literature and state of the art of common projects and techniques. First, is the explanation of the transfer of specific concepts and methods from Geographic Information Science and Technology (GIS&T) to an indoor environment. Second, is the clarification of manufacturing data and the confrontation between manufacturing data and their connection to space and time. Afterwards, the formal data description is investigated by focussing on modelling as ontologies including the theory of affordances, data semantics, the Resource Description Framework (RDF) and the principles of Linked Data. In order to give a detailed insight into the data architecture and representation of semantically annotated manufacturing data, relational databases are described followed by up-to-date graph databases. This is the basis towards a data architecture including data semantics.

2.1 Indoor and Geography :: Definitions, Context and Differentiations

GIS&T applied in an indoor environment is gaining an increased interest, as an average human spends about 90% a day inside buildings (Worboys, 2011; Giudice et al., 2010). This is based on the daily life, as a person sleeps in a building, often works in an office and shopping areas or administrative tasks are done indoor. However, GIS&T follows this step from outdoor to indoor. According to Afyouni et al. (2010), the main cause for GIS&T applied indoor is the need for navigation assistance indoor. In fact, outdoor navigation assistance is well developed based on for example the Global Positioning System as one system of the Global Navigation Satellite Systems, which have already positioning problems in urban areas and are not capable

of indoor positioning (Afyouni et al., 2010). Nowadays, indoor positioning techniques are arising - i.e.: WIFI, Radio Frequency Identification (RFID), Bluetooth Low Energy, Ultra Wide Band, ZigBee, ... - enabling the possibility of applying GIS&T indoor (Afyouni et al., 2010).
The terms indoor, outdoor and geography are defined based on definitions provided by Collins-English-Dictionary (2014). According to Collins-English-Dictionary (2014), '*indoor*' is defined as '*located, used, or existing inside building*'. Contrary, '*outdoor*' refers to '*it does not happen inside a building*'. Both definitions stress the term '*building*' defined as '*something built with a roof and walls, such as a house or a factory*'. '*Geography*' is defined as '*the study of the natural features of the earth's surface, including topography, climate, soil, vegetation, etc, and man's response to them*' or *the natural features of a region*' (Collins-English-Dictionary, 2014). As the interest of GIS&T applied indoor is increasing, the Open Geospatial Consortium (OGC) proposed the IndoorGML standard which defines '*indoor space*' as '*space within one or multiple buildings consisting of architectural components such as entrances, corridors, rooms, doors, and stairs*' (Lee et al., 2014). The standard by Lee et al. (2014) focuses on the space where objects can be located, placed or navigated. Missing is the consideration of architectural components themselves - i.e.: a desk - which have to be considered within modelling approaches such as barriers.
Differences between indoor and outdoor in respect to GIS&T are outlined by Zlatanova et al. (2014). The significant difference between indoor and outdoor complicates especially the orientation of humans (Zlatanova et al., 2014):

- In indoor environments, orientation objects from outdoor are missing such as the sun position, shadows and more.
- Complicated indoor orientation based on building levels, smaller spaces and a difficult overview.
- Indoor, there is a different way of movement with less structured lanes for movement and there is a wider variety of options to go from one room to another.
- Presence of obstacles in indoor spaces, which have to be considered.
- Difficulty of identifying points of interest, which can have various appearances such as a printer or a coffee machine.
- Perception of space is different referring to a slower movement speed.

Zlatanova et al. (2014) present an approach for the subdivision of the indoor space for indoor wayfinding and navigation tasks. They define concepts for the indoor space focusing on navigable and non-navigable areas, the agent and activities. However, figure 2.1 shows a use-case of their approach where the navigable and non-navigable areas are changing. Figure 2.1 shows all passable areas for an agent, which is then modified by activities and events. Therefore, some areas are not accessible due to a missing key and there are dangerous areas where it is still possible to navigate (Zlatanova et al., 2014).

Figure 2.1: *Partitioning of Indoor Spaces (Zlatanova et al., 2014).*

Additionally, the field of application and the context are enablers for GIS&T indoor. Meijers et al. (2005) shows the connection between modelling of the indoor environment which has to consider the structure of the building, functionality and accessibility as well as the field of application. An indoor environment example, spatial modelling and the field of application is presented by Meijers et al. (2005) starting with the question '*What is a door?*' as a not trivial question. The first field of application coins indoor navigation in a public building for administrative tasks with open public doors, closed private doors, restricted areas and emergency exits which are not considered for public indoor wayfinding. By contrast, if the field of application addresses an emergency case or building evacuation, then all doors have to be considered as usable for the purpose of wayfinder. Therefore, all doors have to be considered. Next to doors, also a window can be seen as a door to leave the building in the ground floor, whereas in other floors there is an exception on existing emergency ladders (Meijers et al., 2005).
The combination of GIS&T applied indoor and the context is highlighted by Afyouni et al. (2012). Therefore, figure 2.2 shows the variability of the context and what has to be considered for context aware indoor navigation systems (Afyouni et al., 2012) and spatial indoor modelling. It subsumes the context of use and context of execution. Context of execution focuses on the overall computational environment. The context of use varies on the object of interest, a person, location, action and visualization (Afyouni et al., 2012). This context-awareness has to be kept in mind for the conceptualization as many use-cases have to be considered of manufacturers, which also vary in divisions of the company and their responsibilities.

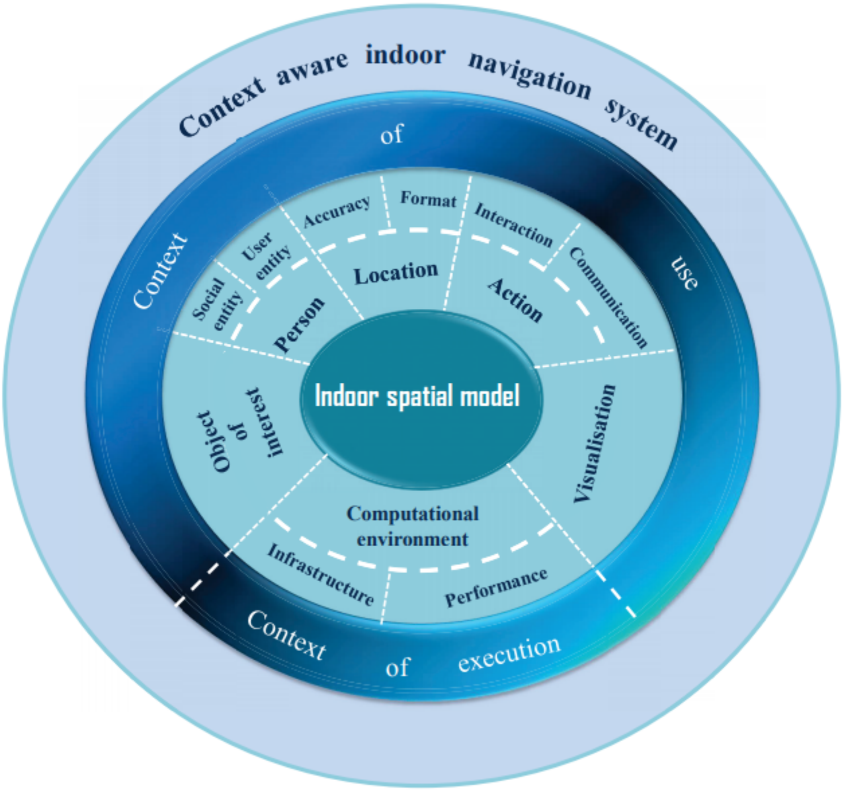


Figure 2.2: *Context Awareness for Indoor Navigation Systems (Afyouni et al., 2012).*

2.2 Manufacturing Data & Spatio-Temporal Data

Manufacturing data are strongly intertwined with spatial, temporal and spatio-temporal data. As outlined in section 1.2, the need for digitization produces more and more manufacturing data referring to space and time. According to Papadias et al. (2002), the importance of spatio-temporal data is increasing. Outdoor spatio-temporal data comprises results from traffic analysis (Papadias et al., 2002). Indoor, Fan et al. (2011) point out that companies gather historical information about movements of assets or different states of an asset/equipment. This is necessary, to replay assets states through the production processes.
One main advantage of spatio-temporal manufacturing data, is the potential for spatio-temporal data mining. This enables analysing and visualizing large datasets (Compieta et al., 2007). This is not a straight forward task and thus it is complex to analyse complex spatio-temporal datasets in an

automatic way (Andrienko et al., 2010). The storage in a spatio-temporal enabled database is unavoidable, to ensure a proper spatio-temporal analysis (Fan et al., 2010). The states of a spatio-temporal object have to be considered, which are presented in figure 2.3. There, Pelekis et al. (2004) show eight states based on the geometry, the topology and the attributes of a spatio-temporal object.

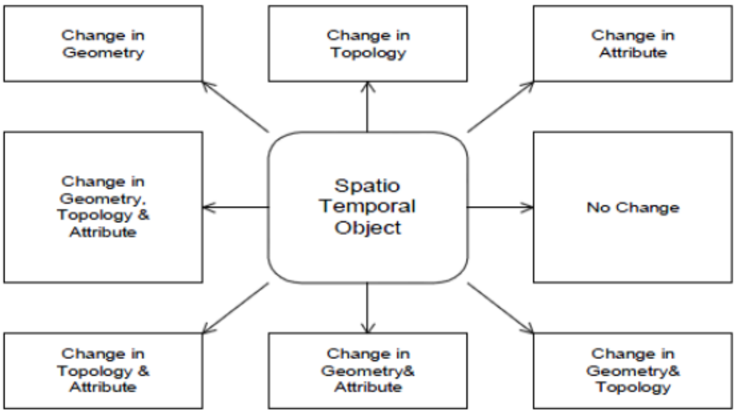


Figure 2.3: *States of a spatio-temporal object (Pelekis et al., 2004).*

Therefore, database modelling for spatio-temporal data and thus manufacturing data is essential. Manufacturing data combine different spatio-temporal data models, which can for example be a '*database model based on time-stamping*', an '*event-oriented data model*' or a '*snapshot model*' (Pelekis et al., 2004; Schneider, 2009). According to Pelekis et al. (2004) and Schneider (2009), each data model supports different tasks and provides different query capabilities. Pelekis et al. (2004) describe a '*database model based on timestamping*' as an approach that tracks the state of an object based on a tuple of timestamps - i.e.: the position tracking of a production asset through the production environment. The advantage is the known state of the production asset at a certain time, whereas it is not known what happened in between. In addition, Pelekis et al. (2004) describe the '*event-oriented data model*' as a logging of object changes or events, storing each individual event. Thus, this database model supports the analysis of every object state with no redundancy, as nothing is stored if there is no event.
To sum up, the storing of spatio-temporal data is complex. If spatio-temporal data represents manufacturing data it is more sophisticated as a spatio-temporal data model has to comprise a mixed database model. It has to consider the '*database model based on timestamping*' for storing the movement behaviour of production assets throughout the production environment. Further, it has to consider the '*event-oriented data model*' as it

stores for example the execution start and end of an asset at an equipment. The necessity of a mixed database model is based on the combination of different locations and the resulting amount of data. If a production asset is delivered to an equipment, it can happen that the localized box of the asset is stored in a shelf and the production asset is brought to the equipment separately (i.e.: in automated areas, the location can vary significantly). As the position of the equipment is known, the location of the equipment represents the actual location of the production asset while processing. Additionally, for the huge amount of movement data time-stamping reduces the amount of data.

2.3 Formal Data Modelling :: Ontologies, Semantics and Linked Data

This section covers data modelling based on ontologies including the theory of affordances used in this research. Additionally, the focus is on data semantics leading to linked data and the RDF.

2.3.1 Ontologies and Data Modelling

Indoor spatial modelling is an important issue for indoor GIS&T related research. Ontologies are a useful way of spatio-temporal modelling discussed in literature since the 1980s (Smith, 2001)). According to Gruber (1993), ontologies are defined as a formal description or specification of a shared conceptualization. Thus, Raubal and Worboys (1999)) induce a domain ontology describing a specific domain in a general way. This results in an abstract definition of the content and the behavior of a part of the physical work in the domains' context (Raubal and Worboys, 1999). Uschold and Gruninger (1996) state that an ontology is a description of concepts and relationships of a given context or universe of discourse.
In fact, the elements of an ontology are entities, relations and applied rules (Davis, 2014). Ontologies nowadays follow standards of the World Wide Web Consortium (W3C) using the Web Ontology Language (OWL). Further, there is also the proof that ontologies are capable of spatial representations and relationships (Grenon and Smith, 2004; Hu and Janowicz, 2016). The modelling of the spatial domain with the help of a (geo)-ontology is also described by Bishr and Kuhn (2000), Frank (2001) and (Hu and Janowicz, 2016). Based on such a formal specification as an ontology, semantic interoperability can be addressed which is described in sub-section 2.3.3. Therefore, the advantage is the top-down approach of ontologies structuring existing data of domains (Hu and Janowicz, 2016).

Types of ontologies are defined by Yang and Worboys (2011) and (Sowa, 2001). Sowa (2001) defines two main options for the classification of ontologies as either a large single ontology or a collection of microworlds. The detailed concept of microworlds is induced by Yang and Worboys (2011) focusing on upper ontologies, domain ontologies, task ontologies and application ontologies illustrated in figure 2.4. Figure 2.4 shows the introduced types of ontologies and their level of detail in terms of a generic conceptualization up to a specific conceptualization. The most generic way is the upper ontology subsuming the domain ontology and the task ontology. The domain ontology describes the environment itself and the task ontology presents a specific task i.e.: a navigation task. The most specific ontology is the application ontology, which is the connection of the domain ontology and the task ontology. This results in one large single ontology comprising the task and the environment (Yang and Worboys, 2011).

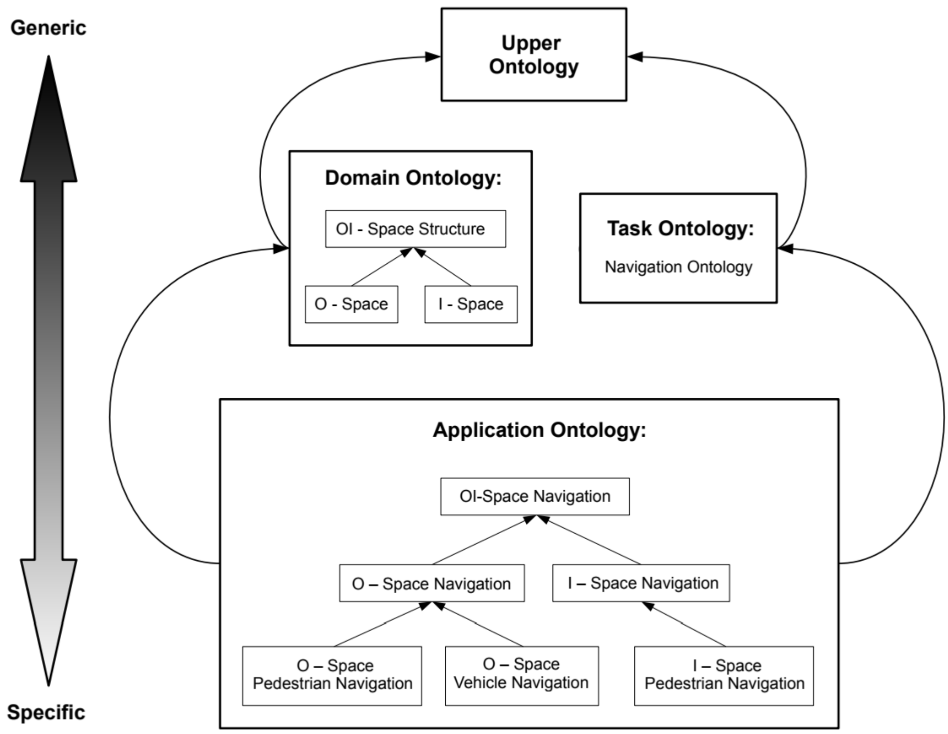


Figure 2.4: *Classification of ontology types from a generic upper ontology to a very specific application ontology (Yang and Worboys, 2011).*

The benefits and advantages are the capability of reuse and the sharing of knowledge, whereas it supports that humans from different expertise talk about the same '*thing*'. Ontologies support the structuring of data and they provide different types of modelling comprising the task and the environment at hand.

2.3.2 Ontologies and Theory of Affordances

The theory of affordances describes relationships between abilities of entities in the environment. Generally, the term affordance is defined by Gibson (1977) and Gibson (2014) focusing on the action of "*to afford* ". The definition is as follows:

"*The affordances of the environment are what it offers the animal, what it provides or furnishes, whether for good or ill.*"(Gibson, 2014, p. 127)

Therefore, the theory of affordances comprises a concept where the "meaning" of objects is considered, which can then be used to satisfy needs of action possibilities to be performed (Gibson, 1977). According to Gibson (1977), affordances are defined by object attributes and additional information including object abilities and properties. This leads to the expression of Koffka (1935): "*Each thing says what it is*" (Koffka, 1935, p. 7).
By respecting the stated definitions, the affordance of a chair is "to sit" as a result of the attributes, capabilities and the properties of the interacting entities (Gibson, 2014). Raubal and Worboys (1999) add the relativeness to the definition of affordance. In the representation of the affordance of a chair "*to sit*" this means: "*It has to be a flat and hard surface with a specific heigt and is relative to the size of an individual*" (Raubal and Worboys, 1999, p. 2). This means for example a chair for a baby does not afford the sitting of an adult.
In order to support GIS&T, Jordan et al. (1998) applied affordances on the modelling of places in GIS. There, places are described based on three aspects i) the agent; ii) the environment; and iii) the task (Jordan et al., 1998). The applied examples focuses on the evaluation of the suitability of restaurants for customers comprising the preferences of an agent (customer) and the task (eating) (Jordan et al., 1998). Another example by Jonietz and Timpf (2013) combines affordances and navigation, therefore the theory of affordances is extended to a spatial suitability model for navigation.
Additionally, affordances are applied in the context of Agent-Based modelling. Raubal (2001) developed a wayfinding simulation in airports, agents need to interpret what the environment offers in a certain relevance for wayfinding capabilities. Raubal and Moratz (2008) additionally developed a model focusing on affordance-based agents. Their research aims on the enabling of robots to identify relevant properties of the environment and the action in respect of the robots' spatio-temporal situation, tasks and capabilities (Raubal and Moratz, 2008). A number of additional research and

studies focus on path planning of agents in order to solve navigation concerns (Kapadia et al., 2009; Kim et al., 2011).
Based on ontologies or formal data modelling, affordances can be incorporated based on relationships of entities and thus on the definition of thresholds. Relationships can then be used to refer to affordances and thus to support the solving of tasks and challenges.

2.3.3 Semantics, Semantic Web Initiatives and Semantics of Geospatial Data

Semantics and semantic annotations focus on the meaning of language and how the meaning can be interpreted (Cruse, 2011). Cruse (2011) states that semantics aim to enrich data with this meaning and thus generate new knowledge. Therefore, the semantic web or web of data is induced.
The Semantic Web or Web of Data (Berners-Lee et al., 2001; Bizer et al., 2009) is a concept that allows data to be shared and reused across applications, enterprises, and community boundaries. In order to enable sharing of data, they have to be provided in a certain format (a photo or scan qualifies as well). Berners-Lee (2006)) denotes the lowest level of data as 1-star data. 1-star data are published on the web in any format with an open license. The highest rating are 5-star data which are data that are published in an open W3C standard (RDF and SPARQL) to identify things including the links to other data sources to generate the context of the data. 5-star data are named as Linked Data (Berners-Lee, 2006).
The advantage of combining semantic annotations and Spatial Data Infrastructure (SDI)s is the reduction of missing or unclear data descriptions leading to misinterpretations (Guarino et al., 1998). Therefore, the interest on geospatial data is growing (Maué and Schade, 2010; Janowicz and Wilkes, 2009). Semantics combined with geospatial datasets support decision makers to identify potential solutions and their alternatives by mapping possible decision onto a map (Janowicz et al., 2010). To correctly represent the geographic space in the conceptual model of an ontology, the relationships of the corresponding ontologies have to be considered and the data linked to the ontology (Janowicz et al., 2010). Janowicz et al. (2010) point out that there is a need for semantic annotations and enhancement of geospatial content.
Current research on the semantic web aims to make the web smarter based on semantics (Bernstein et al., 2016). Today, research of the semantic web focuses on the establishment of linked data which allows links between resources through shared naming (Bernstein et al., 2016). The general focus is set on the representation of semantic web standards, data heterogenity and semantic interoperability and the high volume and velocity of data (Bernstein et al., 2016). This high volume and high velocity data are criteria of

De Mauro et al. (2016), where the term big data is defined. However, the semantic web and the combination with the so-called Internet of Things (IoT) is of huge potential for future applications (Gyrard et al., 2016).
To present this possibility of an interchanging and integrating data infrastucture on the web, we can utilize logics and modelling of ontologies. Thus, ontologies cover on top RDF which is introduced in sub-section 2.3.4. Additionally, sub-section 2.3.5 incorporates linked data, as Bernstein et al. (2016) as it is focus of current research referring to the semantic web.

2.3.4 Resource Description Framework

The RDF data format presents the data as triples in the form of subject, predicate and object, which satisfies the design principles of linked data and the semantic web. Data formatted in this way should conform the Linked Data principles, which ensures that data are machine readable, have a Uniform Resource Identifier (URI) to denote things, use W3C standards (OWL/RDF) and data that link out to other data should use URIs to create an interconnected graph of knowledge. Figure 2.5 shows the presentation of the data triple structure as subject "Stefan", predicate "livesIn"and the object "Austria". Therefore, figure 2.5 also illustrates also the Extensible Markup Language (XML) form of the corresponding RDF statement.

Figure 2.5: *Simple RDF-example clarifying the data triple format in the form of Subject, Predicate and Object and as XML representation.*

Through RDF, it is possible to express semantics, and especially geosemantics (Kuhn, 2005; Janowicz et al., 2013). Generally, Pérez et al. (2009) describe SPARQL as a way to query RDF endpoints in semantic enriched manner. RDF data can be queried using SPARQL (Prud et al., 2011). GeoSPARQL in turn is a spatial extension to SPARQL that enables to query on spatial relationships (Battle and Kolas, 2011; Perry and Herring, 2012). This query possibilities via SPARQL, and GeoSPARQL adds the possibility to query over topological (i.e. spatial) relations. Because RDF data are machine-readable, these data format seems well suited for information sharing and for being shared between different applications. Hence, one could query all water bodies in 1km distance around a road or query all airports near the city of London:

```
PREFIX gn: <http://www.geonames.org/ontology#>
PREFIX xsd: <http://www.w3.org/2001/XMLSchema#>
PREFIX spatial: <http://jena.apache.org/spatial#>
PREFIX geo: <http://www.w3.org/2003/01/geo/wgs84_pos#>

SELECT ?link ?name ?lat ?lon
WHERE
{
        ?link spatial:nearby(51.139725 -0.895386 50 'km') .
        ?link gn:name ?name .
        ?link gn:featureCode gn:S.AIRP .
        ?link geo:lat ?lat .
        ?link geo:long ?lon
}
```

2.3.5 Linked Data and Linked Data Principles

The Linked Data (LD) paradigm is a shift in Geographic Information Science, as it offers a new way of structuring, publishing, discovering, accessing and integrating data (Kuhn et al., 2014). LD are design principles originating from the Semantic Web clarified in sub-section 2.3.3. There, data are represented as triples in the RDF data format - sub-section 2.3.4.
Linked Data denote a summary of concepts to publish, share, reuse and integrate data on the Web. In addition, the concept of LD describes a methodology of publishing structured data in a way that data from different sources can be interlinked with typed links. Furthermore, LD are published in a machine-readable format, in a way that their meaning is explicitly defined, with links to other datasets, and in a way that data can be linked from other datasets too (Berners-Lee et al., 2001; Bizer et al., 2009). Hence, Berners-Lee (2006) published four LD principles:

- URI to denote things
- URI's shall be used, so that things can be referred to and dereferenced
- W3C standards like RDF should be used to provide information
- Data about anything should link out to other data

Kuhn et al. (2014) give an example for LD where they describe the city of Portsmouth as located in the county of Hampshire, which is located in the UK itself. Hence, the city of Portsmouth and Hampshire county are combined with a predicate '*isLocatedIn*', which is similar to a transitive relation in an ontology. By combining the former statement and the fact that Hampshire county '*isLocatedIn*' the UK, we could infer a new statement that the city of Portsmouth is also located in the UK. This example shows that there are three pieces, triples, of information that are combined to form LD. First, there is a subject '*Portsmouth*', a predicate '*isLocatedIn*', and an object '*Hampshire*'. This data link via the predicate '*isLocatedIn*' is machine

readable and the machine understands the meaning. Via a traditional representation of a simple link of Portsmouth on a website of Hampshire does not indicate this connection automatically (Kuhn et al., 2014).
Currently, there is a variety of open LD datasets which are summarized in the Linked Open Data Cloud by Abele et al. (2017). Figure 2.6 shows the Linked Open Data Cloud diagram showing all published linked data sets of the linking open data community covering also other individuals and organisations (Abele et al., 2017).Thus, the Linked Open Data Cloud diagram is based on collected metadata.

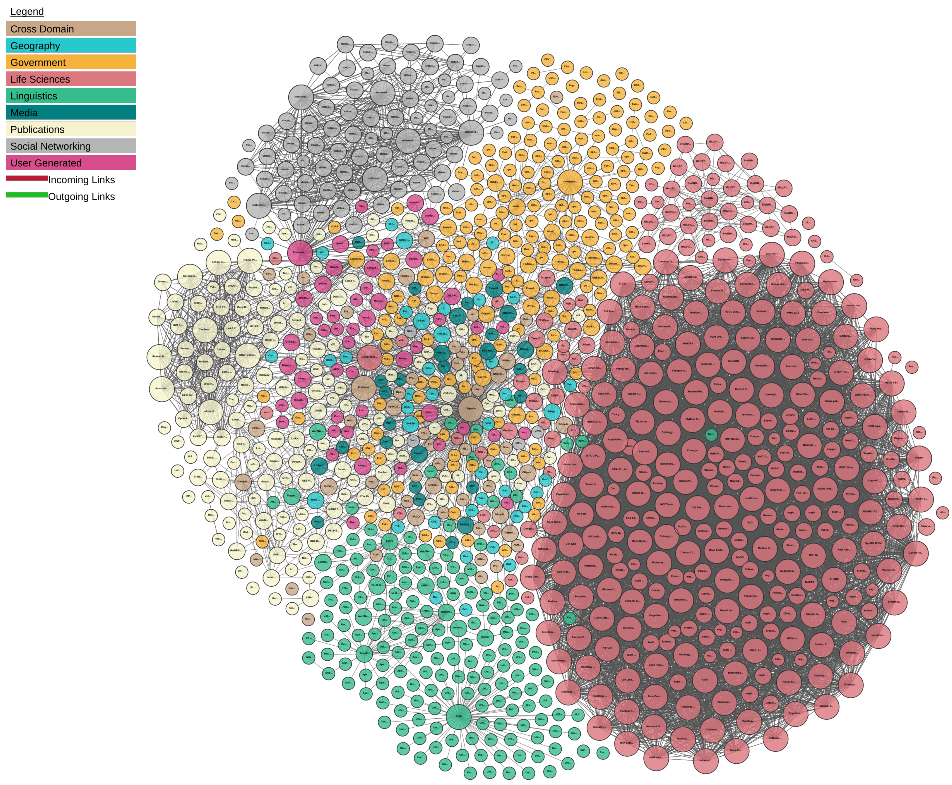


Figure 2.6: *The Linked Open Data Cloud diagram, showing published datasets in the LD format (Abele et al., 2017).*

2.4 Graph Databases :: Towards Semantic Data Representations

This section introduces the fundamentals of graph databases comprising the definition, advantages and a short confrontation of graph databases and relational databases. Further, there is an outline of the used graph database Neo4j.

2.4.1 Graph Databases in General

Within this sub-section, the implementation of a (spatial) graph database is presented as a digital representation of the Universe of Discourse (UoD) as a LD approach. Therefore, a general introduction into graph databases and their potential is given. Beforehand, the applicability of graph databases in the context of GIS&T is proofen by (Lampoltshammer and Wiegand, 2015) which is essentially for the carried out research. Additionally, a graph database also incorporates space and time as one key-issue for manufacturing data (Cattuto et al., 2013; Płuciennik and Płuciennik-Psota, 2014). This leverages the potential of spatio-temporal analysis of a graph database.
To introduce graph databases itself, Robinson et al. (2015) is coined. According to Robinson et al. (2015), a graph is defined as nodes and edges, respectively graph entities as nodes and a description of the relation between entities as edges highlighting the relationship between the graph database model and the real world. This definition of a graph in a database, paves the way for general purposes such as medical history for populations, system of roads or in the carried research an indoor production environment (Robinson et al., 2015). Graphs are a helpful way to understand datasets and the meaning of data enabling semantic representations. Generally, a huge area of interest for graph database is in social networking such as the Google Knowledge Graph, Facebook Open Graph or the Twitter FlockDB (Miller, 2013). Figure 2.7 shows the suitability of graphs for social networks (Robinson et al., 2015). As graph databases are machine readable, the advantage is that they understands the entities' meaning. This can be seen in figure 2.7, Billy follows Harry and vice-versa, Harry follows Ruth and vice-versa, Ruth follows Billy and Billy does not follow Ruth.

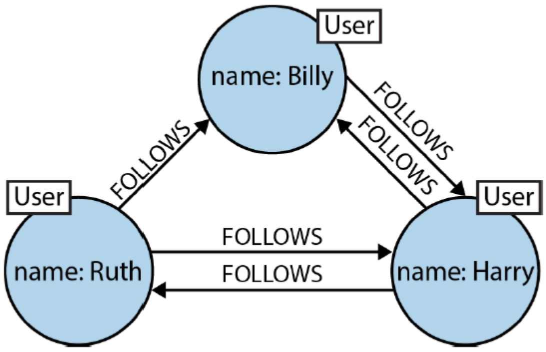


Figure 2.7: *A simple example of a social graph, representing the same principles also for larger graphs (Robinson et al., 2015).*

A graph database has general cabapilities of creating, reading, updating and deleting data in the form of a graph (Robinson et al., 2015). There are three types of graph database models, which are i.) the property graph ii.) the hypergraph and iii.) RDF which is of main interest for the carried out research in terms of the connection of ontologies and graph databases. One main advantage of graph databases in comparison to classical relational databases, is the enhancement of semantics, where relational databases have a lack of relationships (Robinson et al., 2015; Miller, 2013). This is essentially, as datasets are more and more connected and empowered with semantics. According to Robinson et al. (2015), the power of graph databases is the performance of graph databases compared to relational databases, the flexibility through the additivity of graphs and the agility. Therefore, figure 2.8 describes current graph databases comparing the processing and the storage of data in the graph database space from native to non-native. The benefit of native graph processing is the performance of graph traversal, with a possible disadvantage for queries without graph traversal, the maturity of non-native graph databases represents graph databases with a non-graph backend, native graph storage benefits on performance and scalability visualized in figure 2.8 (Robinson et al., 2015).

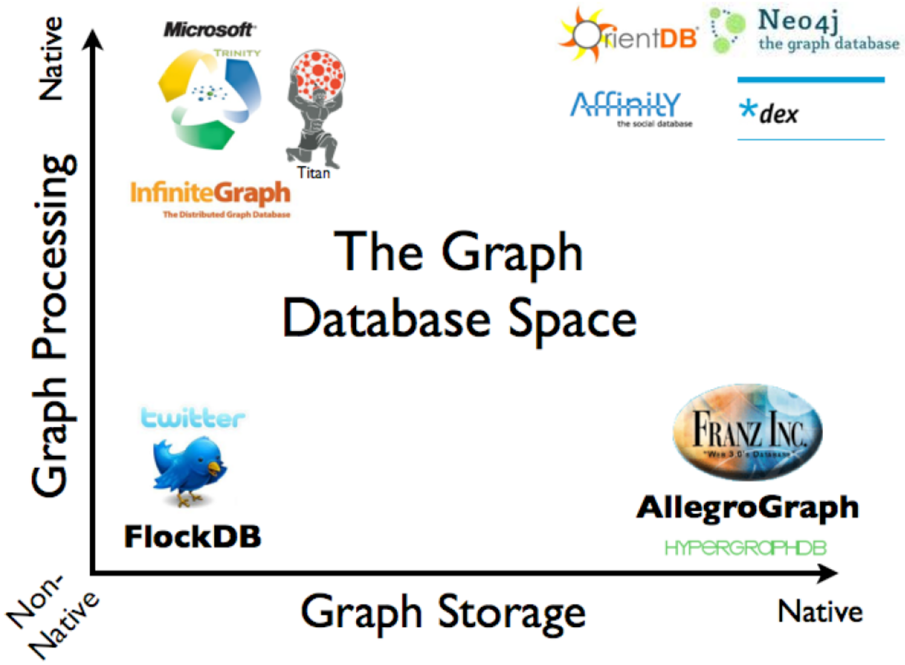


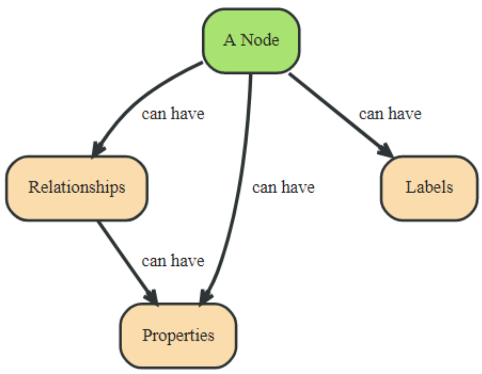
Figure 2.8: *An overview of the graph database space, from non-native to native graph databases (Robinson et al., 2015).*

Miller (2013) concludes, that graph databases will not replace classical relational database management systems at all, because they are suitable for most of the data storage needs. In addition, they are well documented, stable and they provide support options. If the requirements of a database system focus on dynamic and connected data, then a graph database is suggested (Miller, 2013).

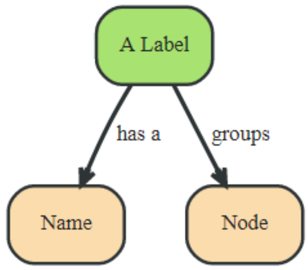
2.4.2 Neo4j - Graph Database

In this research, a neo4j spatial graph database is implemented as linked data approach. Based on the gained expertise from the previous section 2.3 and the previous sub-section 2.4.1, a neo4j graph database is selected which is an alternative to a relational database (Miller, 2013). Next to the general definition of a graph database in sub-section 2.4.1, is a detailed look into the neo4j graph database. According to Robinson et al. (2015), neo4j is a native graph storage and processing environment with the benefit of performance, scalability and graph traversal. In order to query a neo4j graph database, the Sesame Framework is well suited for either querying or storing data (Broekstra et al., 2002). Recently, this Sesame Framework was moved to RDF4J (`https://projects.eclipse.org/projects/technology.rdf4j`),

a successor project. This framework provides capabilities to query data via RDF - described in sub-section 2.3.4 - using SPARQL or GeoSPARL, or via RESTful services.
The first step towards a graph database, is the modelling of the specific domain in a graph data model or by importing an ontology. Thus, the graph data model comprises the RDF data triple format of subject, predicate and object stored as nodes and edges with contained properties. This means, edges represent the predicates also coined as relationships and entities represent subjects and objects which can be differentiated based on their properties. Therefore, figure 2.9 shows all possible entities and their connections in the form of a graph, according to Neo4J (2017). Sub-figure 2.9a represents a node as focal point, which can have relationships, properties and labels. Further, also a relationship can have properties. Sub-figure 2.9b show the abilities of a label, which has a certain name and it can group nodes (Neo4J, 2017).



(a) *Entities of a node.*

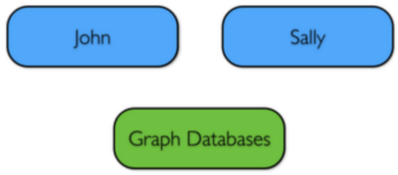


(b) *Entities of a label.*

Figure 2.9: *Entities of a graph database model in neo4j and their relationships Neo4J (2017).*

The neo4j graph database supports the grouping of entities via labels, which is essentially to support the RDF. Therefore, figure 2.10 shows in sub-figure 2.10a the definition of two different groups, the group person (in blue) and the group book (in green). Further, sub-figure 2.10b shows the grouping of nodes based on the label, highlighting that John and Sally are persons and Graph Databases is a book (Neo4J, 2017).

(a) *Definition of two labels as group person and group book.*



(b) *Usage of defined labels from subfigure 2.10a.*

Figure 2.10: *Usage of labels to group objects in neo4j (Neo4J, 2017).*

Based on the gained knowledge, Neo4J (2017) presents an example how all entities are used in a neo4j datamodel visualized in figure 2.11. Figure 2.11 visualizes four nodes which are ‘*Alice*‘, ‘*4FUTURE*‘, ‘*p0815*‘ and ‘*A42*‘, which are classified into ‘*:Person*‘and ‘*:Department*‘ via labels. This means that ‘*Alice*‘ is from the group ‘*:Person*‘ and the other nodes are all from ‘*:Department*‘. The relationships ‘*:BELONGS_TO*‘ give the nodes the meaning that ‘*Alice*‘ somehow belongs to each visualized ‘*:Department*‘. This can also be interpreted by machines (Neo4J, 2017).

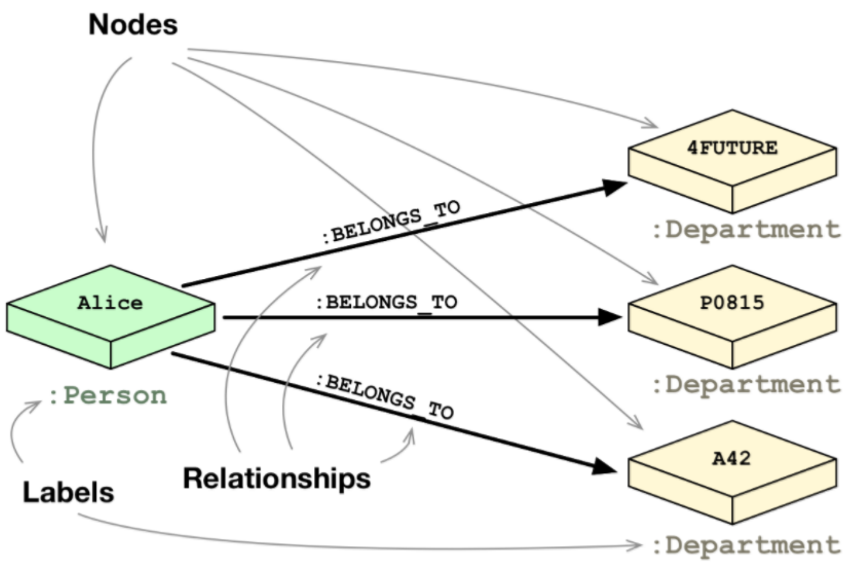


Figure 2.11: *Neo4j data model showing all possible entities (Neo4J, 2017).*

The result of a graph database model filled with the data results in a neo4j property graph (Neo4J, 2017). Therefore, figure 2.12 shows a neo4j property graph presented by Neo4J (2017). In figure 2.12, three types of nodes are included which can be grouped via the label ‘Person‘, ‘Book‘ and

‘*Author*‘. Each person has a property name as for example ‘*Alan*‘ and the books have a book title. The result shows two book nodes, four person nodes and of these four person nodes two are also labelled as authors, which means two persons are also authors. Further, the relationships are ‘*WROTE*‘ and ‘*PURCHASED*‘, whereas the relationship ‘*PURCHASED*‘ has also a date as property, when a person purchased a book. It can immediately be seen, that the ‘*Ian*‘ and ‘*Alan*‘ purchased the same book with the title ‘*Tinker, Tailor, Soldier, Spy*‘ and in addition, Ian purchased a further book ‘*Our man in Havana*‘. However, the meaning can also interpreted by machines, so that a machine knows that the Person ‘*Alan*‘ purchased the book ‘*Tinker, Tailor, Soldier, Spy*‘ on the ‘*05-07-2011*‘ which was written by the Author ‘*John Le Carre*‘. Another advantage of a neo4j graph database is the traversal of a graph. With a graph traversal over the relationship ‘*PURCHASED*‘ it is possible to find a connection between ‘*Ian*‘ and ‘*Alan*‘, as both purchased the same book.

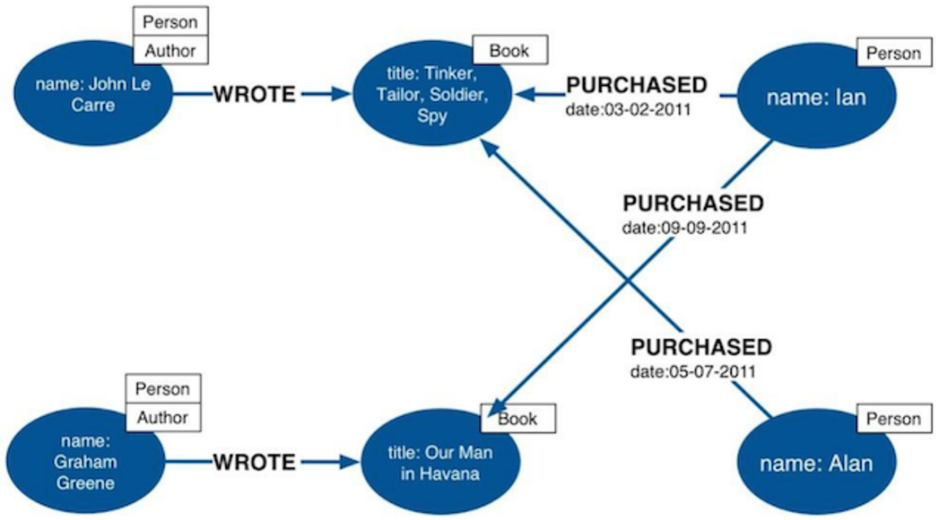


Figure 2.12: *A neo4j graph database model filled with data, resulting in a neo4j property graph (Neo4J, 2017).*

Chapter 3

Methodology and Scientific Approach

This chapter outlines the methodology and the scientific approach, which highlights the connection of different research topics/areas to finally apply Geographic Information Science and Technology (GIS&T) in an indoor production environment. As stated in section 1.8, the dissertation includes publications to show the results of the research. Therefore, this chapter presents the connection between the corresponding publications and lists the main topics of the publications.

3.1 Scientific Approach

The scientific approach is separated into four phases, to proof the application of GIS&T indoor. These four phases are separated into the preparation phase, the modelling phase, the analysis phase and the final phase. The preparation phase starts first and is the general input for the carried out research. This phase mainly concerns the literature review of the corresponding topics of GIS&T indoor. Then, the modelling phase starts with the indoor navigation ontology which influences the Linked Manufacturing Data (LMD) approach. The LMD is also tackled by the literature review of the preparation phase. The LMD approach is the basis for the analysis phase, which covers affordance-based navigation, spatio-temporal analysis and the analysis of parallels between an outdoor and an indoor transportation task. Last, all steps result in the application of GIS&T in the indoor environment of a production company. This conceptual workflow is highlighted in figure 3.1.

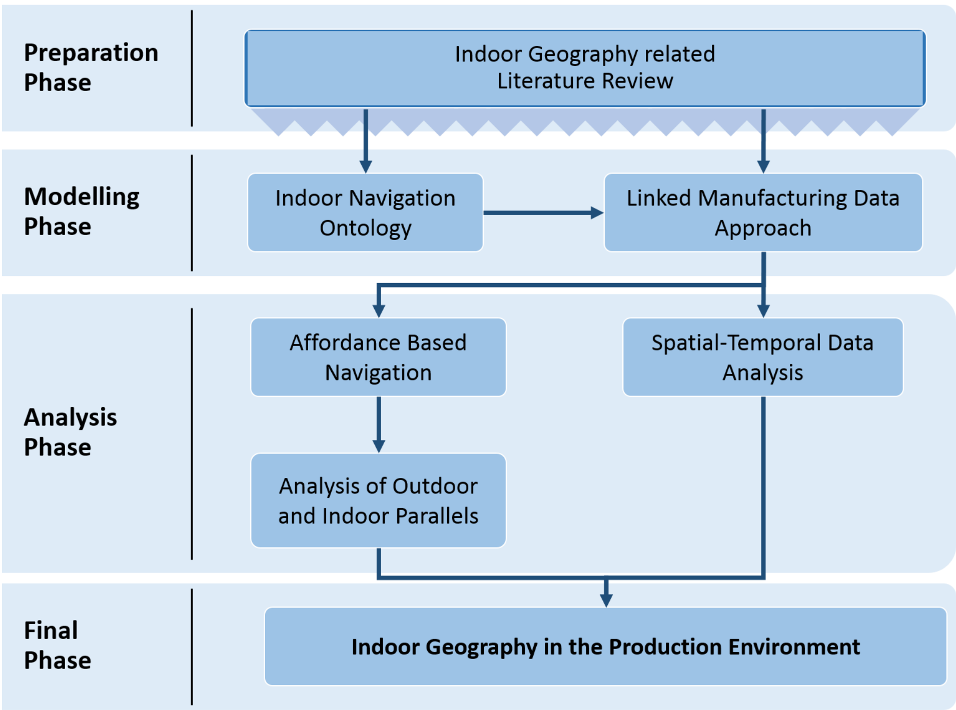


Figure 3.1: *Conceptual Workflow model of the main phases and their connection.*

3.2 Description and Connectivity of Publications

The results of the scientific approach are summarized by scientific publications presented in the chapters 4 to 11. Within these chapters, the chapter title is respectively the title of the publication. Therefore, figure 3.2 summarizes the included publications with the title, the publication type as short-/conference-/journal publication, the main topics according to the scientific approach from section 3.1 and the publication reference.

An Indoor Navigation Ontology for Production Assets in a Production Environment	**Type:** Conference Publication **Topics:** ▪ Indoor Navigation Ontology	**Scholz, J., & Schabus, S. (2014).** An Indoor Navigation Ontology for Production Assets in a Production Environment. *In Geographic Information Science SE - 14; Duckham, M.; Pebesma, E.; Stewart, K.; Frank, A., Eds.; Lecture Notes in Computer Science; Springer International Publishing; Vol. 8728, pp. 204–220.*
Spatial-temporal Patterns of Production Assets in an Indoor Production Environment	**Type:** Short Paper **Topics:** ▪ Indoor Navigation Ontology ▪ Spatial-Temporal Data Analysis	**Schabus, S., Scholz, J., and Skupin, A. (2014),** Spatial-temporal Patterns of Production Assets in an Indoor Production Environment. *In Proceedings of Workshop "Analysis of Movement Data'14" Workshop at GIScience 2014, Poster Presentation, Vienna, Austria. Web: http://blogs.utexas.edu/amd2014/*
A Space in a Space: Connecting Indoor and Outdoor Geography	**Type:** Short Paper **Topics:** ▪ Indoor Navigation Ontology	**Schabus, S., Scholz, J. and Lampoltshammer, T.J. (2015).** *A Space in a Space: Connecting Indoor and Outdoor Geography. 18th AGILE International Conference on Geographic Information Science, 9-12 June 2015 - Lisbon, Portugal; pp. 1–5.*
Geographic Information Science and Technology as key approach to unveil the potential of Industry 4.0	**Type:** Conference Publication **Topics:** ▪ Indoor Navigation Ontology ▪ Spatial-Temporal Data Analysis	**Schabus S. and Scholz J. (2015),** Geographic Information Science and Technology as Key Approach to unveil the Potential of Industry 4.0 - How Location and Time Can Support Smart Manufacturing. *In Proceedings of the 12th International Conference on Informatics in Control, Automation and Robotics (ICINCO-2015), pp. 463-470*
Spatially-Linked Manufacturing Data to support Data Analysis	**Type:** Journal Publication **Topics:** ▪ Indoor Navigation Ontology ▪ Linked Manufacturing Data	**Schabus S. and Scholz J. (2017),** Spatially-Linked Manufacturing Data to Support Data Analysis. GI_Forum 2017, 1, 126-140.
Semantically Annotated Manufacturing Data to support Decision Making in Industry 4.0	**Type:** Conference Publication **Topics:** ▪ Linked Manufacturing Data ▪ Spatial-Temporal Data Analysis	**Schabus, S., & Scholz, J. (2017).** Semantically Annotated Manufacturing Data to support Decision Making in Industry 4.0: A Use-Case Driven Approach. *In Data Science–Analytics and Applications (pp. 97-102). Springer Vieweg, Wiesbaden.*
Mapping Parallels between Outdoor Urban Environments and Indoor Manufacturing Environments	**Type:** Journal Publication **Topics:** ▪ Linked Manufacturing Data ▪ Affordance Based Navigation ▪ Outdoor Indoor Parallels	**Schabus, S., Scholz, J., & Lampoltshammer, T. J. (2017).** Mapping Parallels between Outdoor Urban Environments and Indoor Manufacturing Environments. *ISPRS International Journal of Geo-Information, 6(9), 281.*
Towards an Affordance-Based Ad-hoc Suitability Network for Autonomous Indoor Manufacturing Transport Processes	**Type:** Journal Publication **Topics:** ▪ Linked Manufacturing Data ▪ Affordance Based Navigation	**Scholz, J., & Schabus, S. (2017).** Towards an Affordance-Based Ad-Hoc Suitability Network for Indoor Manufacturing Transportation Processes. *ISPRS International Journal of Geo-Information - Special Issue 3D Indoor Modelling and Navigation, 6(9), 280.*

Figure 3.2: *Detailed description of the publications including the title, type of publication, main topics and the reference.*

According to figure 3.2, figure 3.3 highlights the connectivity of the publications. Therefore, it can be seen that in example the indoor navigation ontology directly emphasizes four publications and thus serves as a basis for these specific four publications.

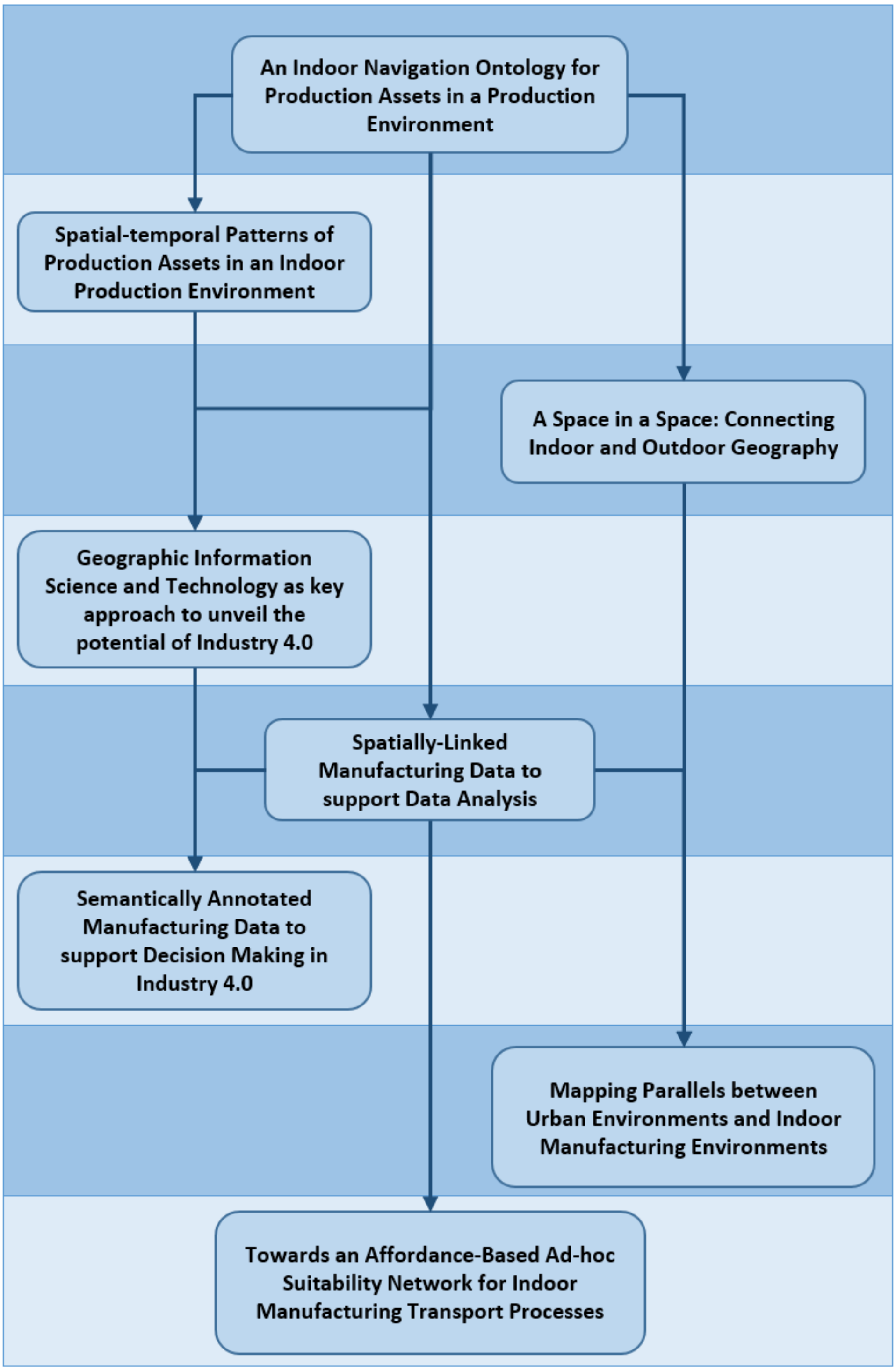


Figure 3.3: *Connectivity of included publications.*

Chapter 4

An Indoor Navigation Ontology for Production Assets in a Production Environment

The first result included as publication, presents an application ontology comprising the indoor navigation task and the indoor environment of the production environment described in section 1.1. Figure 4.1 clarifies publication details and references. The ontology is adapted for the research and is used as a basis for the further results and achievements (Scholz and Schabus, 2014).

Title:	**An Indoor Navigation Ontology for Production Assets in a Production Environment**				
Authors:	**Johannes Scholz** – Research Studios Austria, Studio iSPACE, Salzburg Austria **Stefan Schabus** – Carinthia University of Applied Sciences, School of Geoinformation, Villach, Austria				
Submission Info: (Type, Conference,…)	Full Paper in Geographic Information Science SE – 14 (*peer reviewed*); Lecture Notes in Computer Science, Springer International Publishing Vol. 8728	**Published:** (year)	2014	**Pages:**	18
Reference:	**Scholz, J., & Schabus, S. (2014).** An Indoor Navigation Ontology for Production Assets in a Production Environment. In Geographic Information Science SE - 14; Duckham, M.; Pebesma, E.; Stewart, K.; Frank, A., Eds.; Lecture Notes in Computer Science; Springer International Publishing; Vol. 8728, pp. 204–220.				

Short Description of Authors Activities			
Johannes Scholz:	▪ Wrote the manuscript together with the candidate ▪ Included the concept of Affordances into the Indoor Ontology ▪ Responsible for the revision and the author correspondence	**Stefan Schabus:** (*Candidate*)	▪ Wrote and reviewed the manuscript together with the main author ▪ Mainly developed and described the Ontology (except concept of affordances) ▪ Management of internal release processes

Detailed Description of Candidate (*Stefan Schabus*) - **Activities**

▪ The candidate supported the main author during the writing of the manuscript and provided feedback
  ▪ Focus was set on the indoor production environment and the movement of production assets
▪ The development of the indoor navigation ontology was carried out by the candidate
  ▪ Critical discussions of the concept and improvements were provided of the main author
▪ Implementation of the prototype application for the developed concept
▪ Management of the internal publication release of the production company

Figure 4.1: *Author Activities: An Indoor Navigation Ontology for Production Assets in a Production Environment (Scholz and Schabus, 2014).*

An Indoor Navigation Ontology for Production Assets in a Production Environment

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Abstract This article highlights an indoor navigation ontology for an indoor production environment. The ontology focuses on the movement of production assets in an indoor environment, to support autonomous navigation in the indoor space. Due to the fact that production environments have a different layout than ordinary indoor spaces, like buildings for office or residential use, an ontology focusing on indoor navigation looks different than ontologies in recent publications. Hence, rooms, corridors and doors to separate rooms and corridors are hardly present in an indoor production environment. Furthermore, indoor spaces for production purposes are likely to change in terms of physical layout and in terms of equipment location. The indoor navigation ontology highlighted in this paper utilizes an affordance based approach, which can be exploited for navigation purposes. A brief explanation of the routing methodology based on affordances is given in this paper, to justify the need for an indoor navigation ontology.

1 Introduction

Spatial information systems concentrate on the outdoor space, while humans and things reside indoors and outdoors. Publications show, that an average person spends approximately 90% of their time inside buildings [1]. Compared with the developments for outdoor space, indoor space applications are quite behind and recently got into focus of research and development activities. Worboys [2] highlights the ubiquitous availability of satellite technology (GPS) and aerial photography as utilities used for data collection and positioning in an outdoor space. Due to the emergence and mass market availability of location-based service applications, there is a growing demand for such applications in an indoor environment. Location-based applications in an indoor environment are intended to support people in indoor decision processes – e.g. orientation, navigation and guidance.

The context of a production environment is a special indoor space, as the indoor space is laid out in order to support the production processes best. Hence, a production indoor layout looks different than a piece of architecture constructed for office or residential use. Due to the fact that the purpose of the production indoor space is solely devoted to support efficient production processes there are few fine grained architectural entities that are distinguishable – like rooms. Hence, theory has to cope with non-standard indoor entities that are subject of this paper. Additionally, the positions of equipment can be reordered which alters the layout of the indoor space. This holds especially true for the use case semiconductor industry, which forms the application context of this paper. Due to the fact that any semiconductor production is done in a cleanroom environment, there are several constraints in terms of movements. Not every production asset is allowed to go anywhere in the production line due to cleanroom restrictions, and/or certain production processes which have to be separated due to contamination risks.

In order to support production processes accordingly, there is a need to locate two distinct object classes in the indoor environment: production assets that will undergo several production steps, and production equipment that processes the assets accordingly. In a flexible production environment, like the semiconductor industry, equipment and their positions might change. Either the tool itself is replaced by a new one or the location of a piece of equipment is altered. Additionally, the "production line" is not fulfilling a conveyor belt metaphor with a fixed processing chain. The semiconductor production line is a highly flexible and complex system, due to the following reasons:

- Overall processing time (from raw wafer to electronic chip) of a single production artifact can last from several days to a couple of weeks depending on the product.
- Several hundred production steps necessary until the production is finished.
- High number of different products that require different production steps.
- Each production step can be carried out on several tools which are sometimes geographically dispersed over several production halls – also with varying processing time and quality depending on the equipment used.
- High number of production assets – in different degrees of completion – present in the indoor production line.

The overarching goal is to support the transport processes of production assets in an indoor production environment. With such an approach the current production processes can be supported and an optimized physical layout of the indoor space could be computed by conducting specific simulation runs. In this paper we focus on the navigation and autonomous movement of production assets that shall be supported by means of Geographic Information Science and Technology. Autonomous in this context refers to the ability that each production asset knows explicitly where to go next after a completed processing step. Additionally, the indoor informatics system should be resilient in terms of changes to equipment and indoor spaces. The initial goal is to understand and model the movement of production assets in an indoor production environment. In order to model the movement of production assets an ontology is created that describes indoor space, indoor movements and navigation tasks. Both – indoor space and indoor movements – are necessary in order to fully understand the movement processes possible in the indoor production environment. The ontology is based on the work of Yang and Worboys [3] and Worboys [2].

In this paper we focus on the modeling of movements of production assets in an indoor production environment in order to support autonomous navigation in the indoor space. The environment "production line", which differs from ordinary indoor spaces by the unstable behavior of the indoor entities, requires the movement ontology to look different than in current literature. In order to support autonomous routing in an indoor production environment we utilize the concept of affordances.

The remainder of the paper is structured as follows. In section two the relevant literature is presented, followed by a description of the indoor production environment. This is followed by a section elaborating on the movement behavior of production assets in an indoor production environment, which depends on the description of the indoor production space. Consecutively, we present the indoor movement ontology and extend it towards affordance based routing in an indoor environment in the subsequent section. In the last section we summarize the paper, discuss the results and future work.

2 Relevant Work

This section covers the relevant literature for the paper. First we the highlight relevant work covering indoor geography and switch to indoor geography and production line processes with spatio-temporal data mining in an indoor environment. Additionally, this section covers some literature on affordance-based ontologies for navigation purposes.

A significant number of research activities were carried out over the last decades in the context of modeling outdoor space, providing a rich set of methods high level of structuring and applications. However, indoor geography related research has attained increasing attention during the last years due to the fact that an average person spends about 90% inside a building [1, 4]. Early research works on indoor wayfinding include Raubal and Worboys [5] and Raubal [6]. The work in [6] uses an airport as example of an indoor environment and presents an agent-based indoor wayfinding simulation.

In order to model indoor spaces there exist several approaches that use topology, where the indoor space is "reduced" to a graph [5, 7, 8, 9]. Jensen et al. [10] employ a graph based model to track entities in an indoor environment by placing sensors in the indoor space. To model the 3D geometry of buildings Building Information Systems are used, which do not support navigation and routing in general [11]. Worboys [2] mentions hybrid models that include geometrical and topological features, which are well studied in literature [12, 13, 14]. Other approaches provide different levels of granularity of the indoor space. Hence, the user can rely on more details for important points on a journey which requires route generation and visualization in one application [15, 16, 17].

Production line processes represent a challenging research and application field for indoor geography. Due to the fact that any optimization of production processes is depending on allocation and sequencing of production processes. Such optimization can increase the efficiency of production processes and therefore provide an interesting option for cost savings based on an increase of performance and productivity [18, 19, 20]. An increase of productivity can also be realized by analyzing spatio-temporal data, which are generated by storing historical information on production processes. Data mining methods are appropriate to analyze spatio-temporal data accordingly [21]. In order to create maps to visually analyze such data, geovisual analytics can be employed [22]. The main advantage is that a person has the ability to recognize visual patterns [23].

In order to model indoor movement of production assets we use ontologies to formally describe the behavior. Ontologies try to determine the "various types and categories of objects and relations in all realms of being" [24]. A domain ontology describes what is in the specific domain in a general way, resulting in a formal description of the content and the behavior of a part of the physical world [6]. Davis [25] lists the elements of a domain ontology: entities, relations and the rules applied. The theory of affordances is used to model routing and navigation of production assets, as they should be able to move in an autonomous manner, requiring the detection of the best possible path with respect to given constraints. The term "affordances" is coined by Gibson [26, 27]. Affordances and ontologies have been subject to research in outdoor and indoor environments [28, 29, 30]. While Anagnostopoulos et al. [31] and Tsetsos et al. [32] develop an indoor space ontology focusing on navigation, Yang and Worboys [3] develop an ontology for indoor-outdoor space. They separate different "microworlds" by distinguishing between the upper level ontology, domain ontology and a task ontology. The navigation ontology developed in this paper inherits elements describing the indoor space in order partially integrate indoor space entities in the navigation ontology. Hence, the approach in this paper includes a task and domain ontology – indoor space – with respect to Yang and Worboys [3]. Hence, the work here can be related and integrated in the upper as well as the indoor space and task ontology published in [3].

3 Indoor Production Environment

This section describes the indoor production environment under review. As previously mentioned, the objective of this paper is the modeling of production assets in a semiconductor fabrication. Such an indoor environment has several peculiarities that distinguish it from other production environments and ordinary indoor spaces. This section is based on the work of Geng [33], Osswald et al. [34] and personal experience.

Any semiconductor fabrication has to be operated in a clean room environment that ensures a low proportion of contaminating particles – both in size and quantity. Due to the fact that clean room space is expensive to construct and maintain, clean rooms are designed to be as compact as possible for the chosen equipment to be placed inside. Hence, the space dedicated to movement (people and production assets) and storage of production assets is limited. In addition, different quality classes of clean rooms exist, that are distinguishable by air quality (particles per m^3 air). Generally, the changeover between different clean room quality classes – often adjacent – is not easily possible. While it is allowed to switch to a clean room of lower quality at any time through doors, the switch to a clean room of higher quality is only possible through special airlock. This is especially true for the process of entering a clean room environment, which is only possible via specific airlocks. Hence, any humans – i.e. operators – can only leave and enter a production line using the airlocks. Similar, production assets can only enter the clean room at a specific airlock designed for production assets and are thoroughly cleaned thereafter, in order to prevent any contamination in the main production line.

The movement of operators and production assets is additionally restricted to other quality issues. Specific production asset types are prone to contamination due to chemical processes which are a result of certain production processes. Hence, selected production assets are not allowed to enter or leave a certain area of the production line to prevent them from contamination. As the production is located on different floors there are several possibilities to switch floors. Some staircases can be used by operators carrying production assets, while others can only be used by operators. In general production assets change floors by using elevators.

The indoor space under review is highly unstable, due to constant change of market demand and, thus altered production necessities. Hence, equipment has to be relocated, removed or new equipment is brought into the production facility. These processes can result in an altered layout of the indoor space, as corridors might change according to the space needed for certain equipment. This has consequences for the navigation of production assets as the "best" paths connecting two devices are altered.

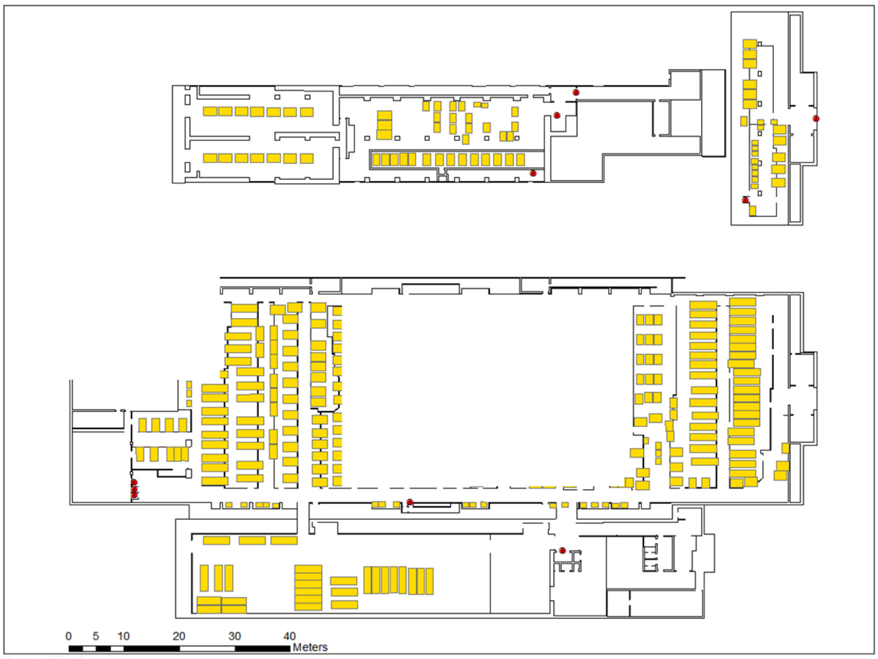

Fig. 1. Indoor space layout of the semiconductor production which is subject of this paper. Yellow rectangles represent devices in the clean room, and red dots represent transfer nodes. The white spaces are intentionally to disguise the complete production layout.

Generally, the layout of the production hall differs from classical production environments and ordinary indoor environments. Office or residential buildings' indoor space can be divided into rooms and corridors that are connected by doors. In a semiconductor environment, rooms are hardly present due to the fact that the indoor space is organized in distinguishable corridors with considerable length (see Fig. 1).

The production of microchips is a complex process chain that involves several hundred different production steps not aligned on a conveyor belt. Hence, there movement processes have a multifaceted structure due to a multitude of different microchip types having different production process chains. Additionally, each production step can possibly be done on several tools which increases the flexibility in terms of production, and increases the complexity of the movement behavior. In addition, the equipment suitable for a certain production step may be geographically dispersed. Nevertheless, each microchip type has a specific production plan that defines the process chain. Hence, each production asset in the clean room has a certain grade of completion and the next production step can easily be determined.

The indoor production line under review consists of one production hall of an Austrian semiconductor manufacturer. The layout of the indoor space is depicted in Fig. 1, showing the equipment positions as yellow and blue rectangles. In order to track production assets accordingly, an indoor tracking system called LotTrack is employed that relies on RFID and ultrasound technology. A detailed description of the system, the rationale behind the utilized technology and the application itself is found in [35].

4 Movement of Production Assets

In order to model the movement of production assets in an indoor environment, we start with a monitoring of the current in-situ "behavior" of production assets. The evaluation of trajectories collected gives insight in the behavior and helps shaping the navigation ontology accordingly. Thus, the following section elaborates on the movement behavior of production assets in the indoor environment. It is intended to show that we can model the movement of the agents using a graph, consisting of edges and nodes respectively.

The hypothesis regarding the movement is that production assets are moving along the corridors, most probably along the centerline of a corridor. Hence, the positions of production assets are compared with a graph consisting of corridor center lines and connection lines to equipment only in areas that are traversable by humans and production assets (see Fig. 2). To evaluate the spatial nearness between gathered asset positions and the graph a 1m buffer around the graph is created. In total a number of 41097 position recordings are tested (see Fig. 3) with respect to the buffer zone. In total 97.3% of the positions are inside the network buffer of 1m.

Problematic in this respect is the position of the antennas used to gather the production assets' position. The positioning antennas are placed on the ceiling with special rails and the positioning algorithm of LotTrack snaps positions to the nearest antenna rail. Hence, any tracked positions are generally shifted.

The evaluation of tracked positions of production assets as well as the layout of the indoor space – i.e. corridors – gives evidence that movements can be modeled utilizing a graph [7, 8, 9]. The graph used to model the movement of assets comprises of nodes and edges, which are described in detail in the navigation ontology in section 5.

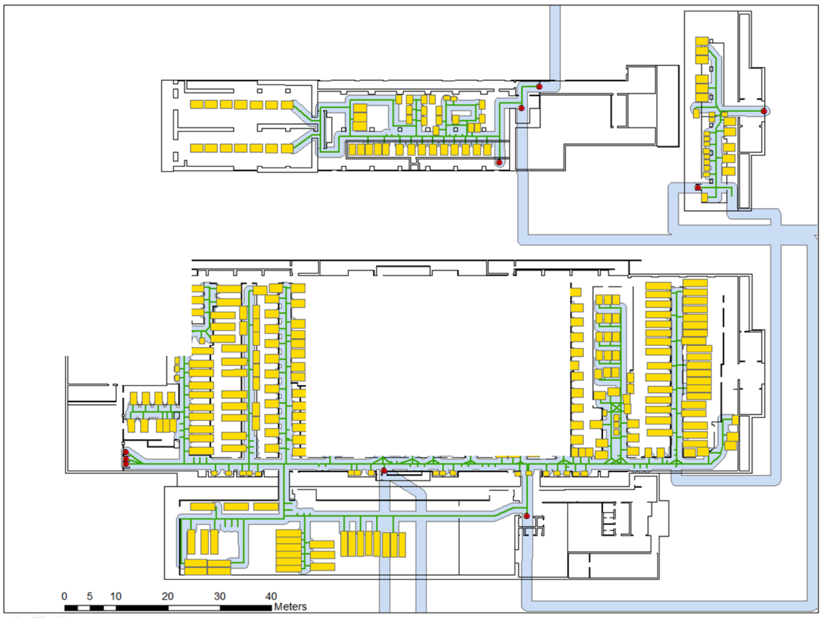

Fig. 2. Indoor space of the production hall under review. The green line represents the network that is traversable by humans and production assets, whereas the blue areas mark a 1m buffer around the network. Blue areas without green network lines are intentionally created, and represent the "virtual" connection of transfer nodes. The white spaces are intentionally to disguise the complete production layout.

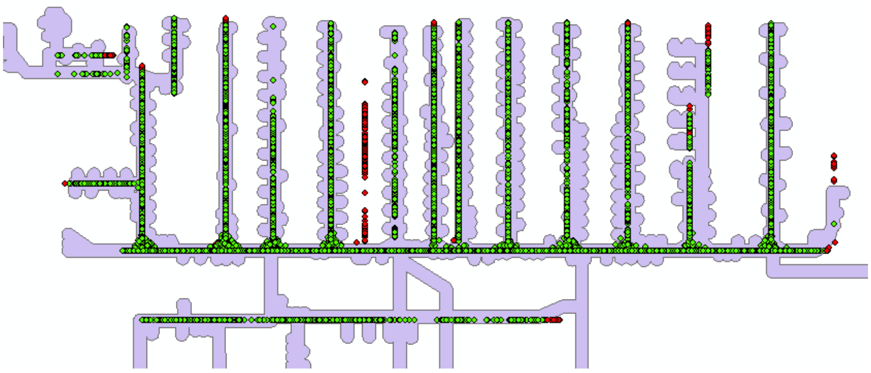

Fig. 3. Tracked production asset positions (approx. 41000) in relation to the 1m buffer around the network (marked in purple). The network positions are marked in green if they are inside the buffer and red if outside.

5 Affordance-based Indoor Navigation Ontology for Production Environments

Creating the navigation ontology for production assets is closely related to the work of Yang and Worboys [3]. The navigation ontology developed in this paper inherits also elements describing the indoor space in order to have an integration of the navigation ontology and indoor space entities. The ontology developed here is based on affordance theory [26, 27] which can be used to establish connections between indoor and outdoor space. In addition, we employ the theory proposed by Jonietz and Timpf [36] of an affordance-based simulation framework for spatial suitability for navigation purposes.

5.1 Indoor Navigation Ontology

The indoor navigation ontology for production assets is presented in the following section. The ontology is depicted in Fig. 4 providing an overview of the model itself. The definitions of the concepts are given in this section.

Production Unit: A production unit represents the whole equipment of a production line. For example a Facility or a Device that are used during the various production steps. The subclasses are *ProductionUnit_Facility* and *ProductionUnit_Device*.

- *ProductionUnit_Device:* A device is the production unit used for the processing of goods. The device has a fixed position in the production line.
- *ProductionUnit_Facility:* The facility supports transport processes in the production line. The goods can be placed on shelves or tables if they are waiting to be processed or transported. The subclasses of a facility are *ProductionUnit_Facility_Moveable* and *ProductionUnit_Facility_Fixed*.
  - *ProductionUnit_Facility_Moveable:* A moveable facility is used to support a high stock of goods in the production line. They are e.g. bottleneck shelves used to store an extra amount of production assets. Such objects are removed if the stock in the production line is decreasing.
  - *ProductionUnit_Facility_Fixed:* Fixed facilities represent tables, shelves and other not moveable equipment in the production line.

Barrier: A barrier is limiting the transportation or movement behavior in the production line. The subclasses are *Barrier_Fixed* and *Barrier_Moveable*.

- *Barrier_Fixed:* A fixed barrier is limiting the movement behavior and cannot be changed very easily. Subclasses are *Barrier_Fixed_Wall*, *Barrier_Fixed_ProductionDevice* and *Barrier_Fixed_AirQuality*,
  - *Barrier_Fixed_Wall:* A wall is a fixed barrier. It is limiting the transport behavior within a production line.
  - *Barrier_Fixed_ProductionDevice:* The device in a production unit is linked with several infrastructure items such as electricity and gas lines and is regarded as a fixed or not easily changeable barrier.

- *Barrier_Fixed_AirQuality:* For several production goods the air quality in a clean room is of importance and is also a barrier for the transport and movement behavior.

– Barrier_Moveable: Moveable barriers represent mainly barriers that can change over time very easily. The subclasses are *Barrier_Moveable_ProductionFacility* and *Barrier_Moveable_Contamination*.
  - *Barrier_Moveable_Contamination:* A contamination is a barrier over time. Hence, a certain production good is not allowed to enter a specific area of the production line.
  - *Barrier_Moveable_ProductionFacility:* Any production facility can impede movement as it is limiting the space for transportation. E.g. The position of shelves may easily be changed if they are not necessary anymore.

AccessNode: An AccessNode is linking outdoor and indoor space or vice versa. The subclasses are *AccessNode_Outdoor2Indoor*, *AccessNode_Indoor2Indoor* and *AccessNode_Indoor2IndoorTransfer*.

– *AccessNode_Outdoor2Indoor:* The connection from outdoor geography into the indoor environment. Therefore, the subclasses *Entrance*, *Exit* and *EntranceExit* are necessary.
  - *AccessNode_Outdoor2Indoor_Exit:* The exit is representing the way from an indoor geography back to the outdoor geography. This is necessary as there exist designated doors for leaving a production line (especially true for a production environment with clean rooms)
  - *AccessNode_Outdoor2Indoor_EntranceExit:* The EntranceExit represents both the way from outdoor geography to indoor geography and backwards.
  - *AccessNode_Outdoor2Indoor_Entrance:* The entrance enables the interaction and movement from outdoor into the indoor space.

– *AccessNode_Indoor2IndoorTransfer:* The transfer indoor is representing the connection in the same indoor space, thus connecting e.g. different floors.
  - *AccessNode_Indoor2IndoorTransfer_Elevator:* The transfer of production assets with an elevator in order to change the floor level.
    - *AccessNode_Indoor2IndoorTransfer_Elevator_TimeDependend:* The time dependence of an elevator is used in order to integrate the average waiting time until an elevator is available, due to the fact that elevators are mostly not available instantaneously.
  - *AccessNode_Indoor2IndoorTransfer_Stair:* A stair enables the transfer between different floors in an indoor space.
    - *AccessNode_Indoor2IndoorTransfer_Stair_NonRestricted:* Traversing a stair is allowed for all production asset types.
    - *AccessNode_Indoor2IndoorTransfer_Stair_Restricted:* The traversal of a stair is not allowed for certain production asset types.

– *AccessNode_Indoor2Indoor:* This class represents the transfer between different indoor spaces – e.g. different production halls.
  - *AccessNode_Indoor2Indoor_QualityCheckpoint:* A quality check such as an e.g. air quality check with an airlock.

- *AccessNode_Indoor2Indoor_SecurityCheckpoint:* The entrance to certain areas can be restricted.

Corridor: A corridor is describing and including the ways where an operator – i.e. human being – can walk and transport the production goods in the production line. The subclasses are *Corridor_Node*, *Corridor_Passage* and *Corridor_Entrance*.

- *Corridor_Node:* Corridor nodes include the starting point, end point or interaction point of a navigation process.
  - *Corridor_Node_ProductionFacility:* A start point, end point or interaction point can be a production facility. For example a good has to be brought to a shelf because something has to be controlled.
  - *Corridor_Node_ProductionDevice:* A production device is mainly a start or end point for the transportation or navigation as the production goods are processed here.
- *Corridor_Passage:* The passage itself is representing the way between two consecutive navigation tasks.
  - *Corridor_Passage_Edge:* An edge is used between the different nodes and is combined to a passage along the corridor.
- *Corridor_Entrance:* Corridors need entrance points to the network for navigation and transportation in the production line.
  - *Corridor_Entrance_AccessNode:* The access node is one opportunity where operators or production assets are accessing the transportation network.
  - *Corridor_Entrance_Node:* Entrance nodes can also be production devices or facilities.

Navigation_Event: Any navigation task is described through the classes *Navigation_End*, *Navigation_Start* and *Navigation_Turn*.

- *Navigation_End:* This class represents the destination of a transportation or navigation task.
  - *Navigation_End_AccessNode:* An access node is the destination node of the navigation process if e.g. a production asset leaves the production line.
  - *Navigation_End_ProductionUnit:* The transportation between devices or facilities implies that a production facility or device is the end of the navigation task.
- *Navigation_Start:* The navigation start is representing the start of a navigation task, which can either be an *AccessNode* or a *ProductionUnit*.
  - *Navigation_Start_AccessNode:* An access node is the start of the navigation if a production asset is entering the production line.
  - *Navigation_Start_ProductionUnit:* The production unit is a starting point for the navigation.
- *Navigation_Turn:* During the navigation a production asset can perform several actions. These actions are the subclasses *Navigation_Turn_Right*, *Navigation_Turn_Left*, *Navigation_Turn_Backward* and *Navigation_Turn_Forward*.
  - *Navigation_Turn_Right:* The production asset turns right.
  - *Navigation_Turn_Left:* Represents a turn to the left.

- *Navigation_Turn_Backward:* This event is a turn backward or represents backwards moving.
- *Navigation_Turn_Forward:* This is a move forward.

Navigation_Agent: The agent that is navigating through the indoor space.

– *Production_Asset:* This class represents the navigation agent, and encompasses various types of production assets with different properties that have an influence on the suitability of a certain route and the choice of a certain route.

Navigation_Structure: This class contains generic entities that are necessary for route calculation proposes. A sequence of instances of the subclasses *Navigation_Node* and *Navigation_Edge* on which an agent moves defines a *Navigation_Path*. The objects of the class *Navigation_Structure* are help to specify the indoor space entities in terms of representation in a graph with nodes and edges.

5.2 Affordance-based Routing

The navigation of production assets is based on affordances offered by the objects in indoor space with an approach similar to [36]. Affordances, initially coined Gibson [26, 27], describes a concept where an object offers its meaning. Gibson [27] further specifies the concept, that an affordance is not only defined by attributes of an object, but also by the abilities and properties of the interacting object [36]. In this context this approach is applied to the relations of machines and production assets with respect to their properties respectively.
For the case of production assets, several types of assets with specific properties exist that have to be respected when navigating. In addition, in order to define a navigation task the determination of a destination point – i.e. equipment offering a certain production process – and the selection of an appropriate path has to be carried out. This section gives only a rough overview of the algorithm in order to give an impression on the usage of the indoor navigation ontology.

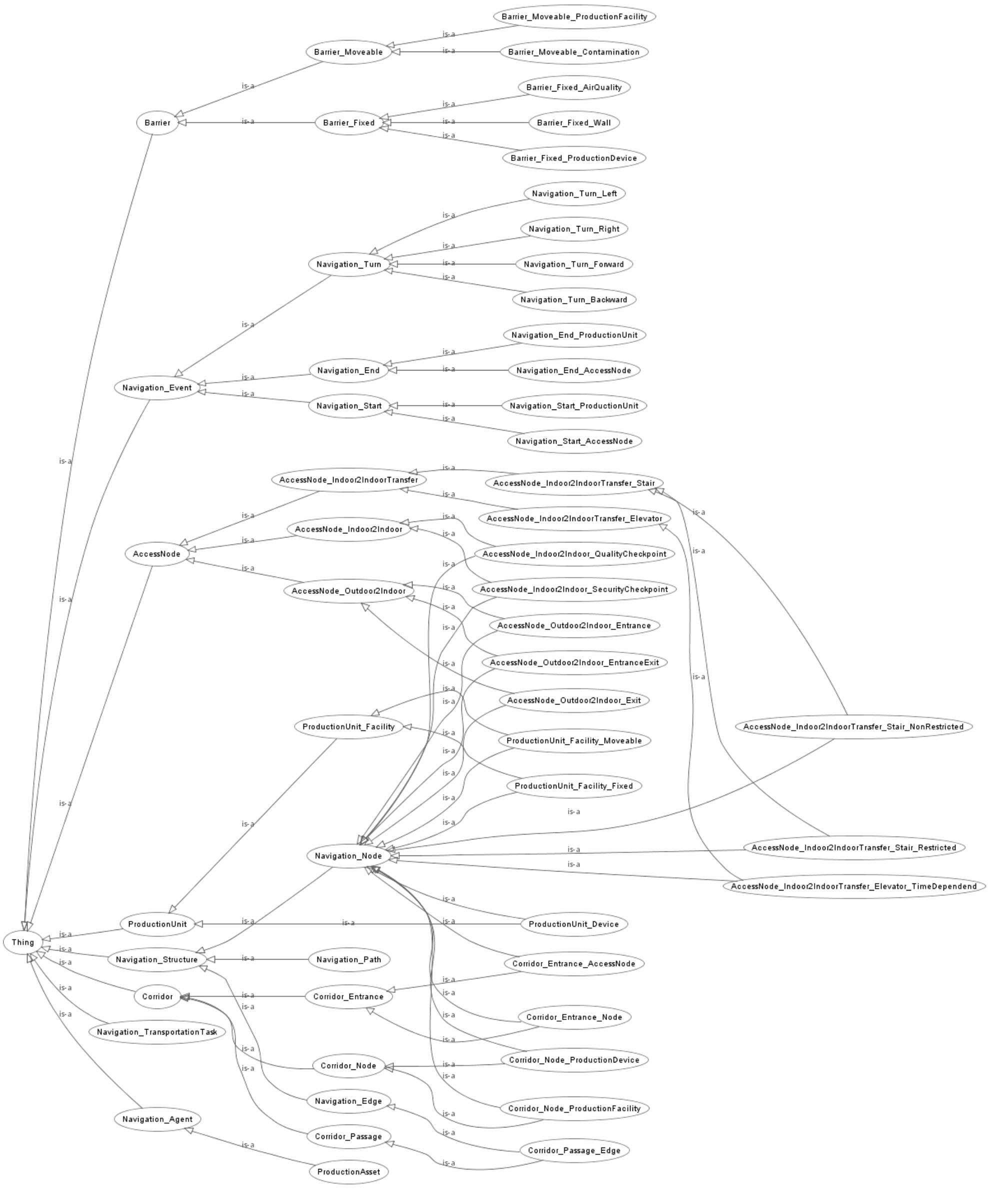

Fig. 4. Navigation ontology for indoor production space focusing on the movement of production assets.

In order to facilitate autonomous navigation of production assets in a semiconductor production environment each instance of the class *ProductionAsset* has certain characteristics:

- Product type: The product type reveals information on possible means of transport (e.g. thin wafer shall be carefully handled [i.e. only elevator, no stairs], 300mm wafers can withstand a low quality clean room due to a specialized plastic enclosure, with 300mm wafers it is not possible to open doors due to the weight of wafers including the plastic enclosure). In addition, the product type reveals information on barriers (quality, contamination) applicable that impede movement.
- List of production processes: This holds information on the sequence of production processes that have to be carried out. Due to the fact that certain processes can be done on several machines, with different processing results in terms of quality, each production asset has to select the piece of equipment that fulfills the requirements “best”.

To support navigation processes in an indoor production space we apply the framework laid out in Fig. 5, which shares similarities with the approach of Jonietz and Timpf [36]. The methodology comprises of the collection of actions of a single production asset – e.g. move to the next production step “cleaning” starting from equipment “etcher_12”. In order to determine the sub-actions contained in an action, the framework starts to analyze the destination production step of the action and moves towards the start point until the starting point is reached. For the action ‘move to the next production step “cleaning” starting from equipment “etcher_12”’ the approach starts to find indoor entities offering the production step “cleaning”. If there is one piece of equipment affording the process of “cleaning” the algorithm analyzes the properties of the cleaning equipment, the start equipment “etcher_12” and the production asset. This results in differences in terms of indoor location – e.g. equipment located on different floors – and/or additional properties that have to be respected – e.g. thin wafers, where no stairs are allowed. Based on the differences and properties of indoor space entities and production assets the sub-actions are determined, starting from the destination equipment towards the start node. Based on the sub-actions found, the algorithm determines the nodes offering the required movement processes. E.g. a sub-action ‘change from floor 1 to floor 2 with an elevator’ searches for a node offering a connecting floor 1 and 2 by an elevator. This process finally results in a set of candidate nodes that are the basis for the navigation of the production assets.

Based on the set of candidate nodes a routing algorithm calculates the “best” route which will be traversed by the production asset. First, candidate routes from start node to target node are determined and evaluated regarding overall route cost. Costs in this respect could be time, overall path length, or any other metric applied. Finally, the route with the lowest cost is returned.

Fig. 6 shows an application prototype for affordance based routing in the indoor production environment. There a production asset starts at an entrance node – labeled with 1 – and has 5 actions to perform, i.e. navigate to five devices in a certain order, where equipment 6 is located on a different floor. In addition, the production asset requires to be moved with care, thus the transition between the floors must be done with an elevator.

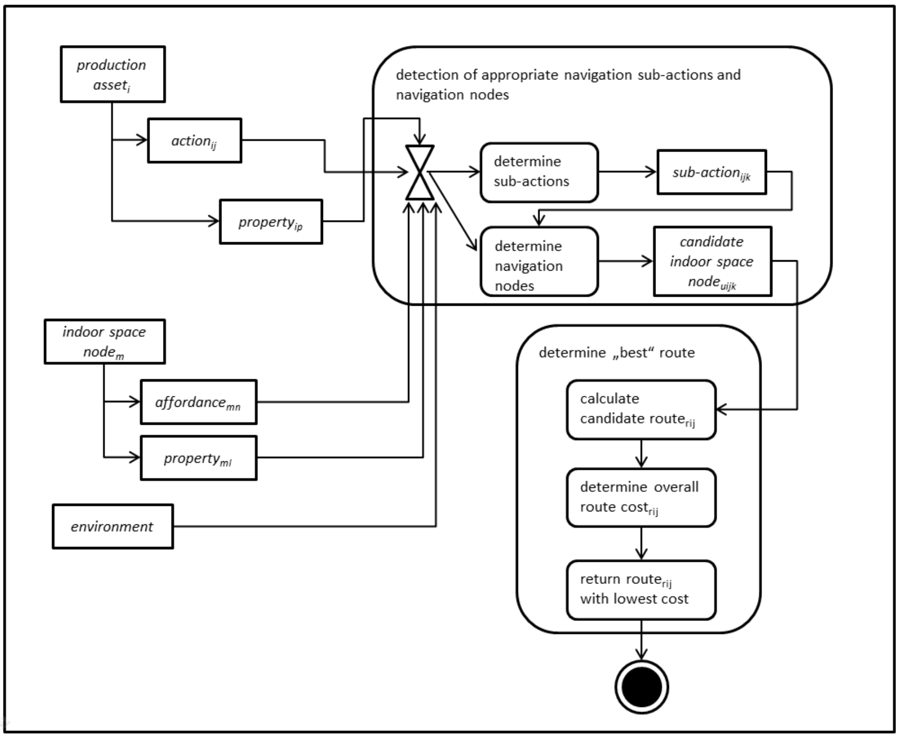

Fig. 5. General approach employed in navigating indoor space based on affordances.

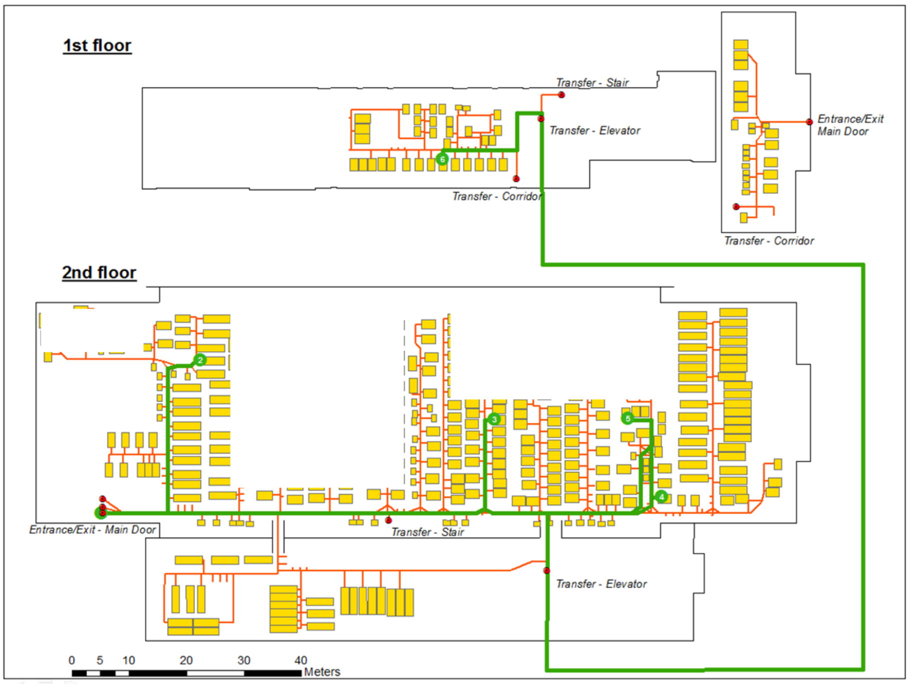

Fig. 6. Prototype application for affordance based routing in an indoor production environment. The red lines represent the traversable graph, and the green lines the route for the production asset. Five actions starting from the main entrance exist that have to be carried out, which are labeled with numbers in ascending order (start node is labeled with 1, final end node is labeled with 6). Of interest is the mandatory transfer from floor 2 to floor 1 by elevator. The white spaces are intentionally to disguise the complete production layout.

6 Conclusion and Discussion

The article elaborates on an ontology for indoor navigation in a production environment – semiconductor manufacturing. The agents moving in the indoor space are production assets that undergo several production processes, which are not aligned sequentially on a conveyor belt. Hence, any production assets should autonomously navigate from one production step to the next with respect to properties of the production asset and the indoor environment. The ontology describing indoor navigation processes is affordance based and includes a description of the indoor space. Based on the results an affordance based routing methodology is outlined and applied in a prototypical application.

The indoor ontology of a production indoor space looks different than current approaches [3] because the indoor space of production environments has different entities than ordinary indoor spaces. Ordinary indoor spaces comprise of rooms, corridors, doors, etc. while the production environment in semiconductor operates in a cleanroom and consists of mainly corridors without e.g. doors or distinct rooms. Due to the fact that production assets should be able to navigate between production equipment, machinery present in the indoor space, barriers (fixed and temporary) impeding movement, and any transfer between different floors are part of the ontology. In addition, the traversable space is modeled as graph that connects elements present in the indoor space. For navigation purposes an affordance based approach is proposed, that identifies required actions and detects nodes that afford the requirements, i.e. transfer from floor 1 to floor 2.

Future research directions include connections between indoor and outdoor space – already mentioned in [3]. In addition, the navigation and movement patterns in an indoor production environment are subject to further research that can be used to evaluate the navigation ontology. To do so we intend to use the concept of Self-organizing Maps [38, 39] and spatio-temporal data mining methods for trajectory pattern mining. Furthermore, we plan to use SOM and analysis of the geographic and attribute space applying the TRI-space approach [37]. In order to focus on the affordance-based routing approach presented in this paper a study highlighting general results of affordance-based routing in comparison to contemporary routing methods.

7 Acknowledgements

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Chapter 5

Spatial-Temporal Patterns of Production Assets in an Indoor Production Environment

Spatial-temporal patterns of production assets are analysed based on the movement behaviour and quality issues taking place in an indoor production environment. Self-Organizing Maps (SOMs) are utilized to identify patterns in the physical space, the attributive space and the time. Figure 5.1 states publication details, the description of authors activities and references (Schabus et al., 2014).

Title:	**Spatial-Temporal Patterns of Production Assets in an Indoor Production Environment**				
Authors:	**Stefan Schabus** – Carinthia University of Applied Sciences, School of Geoinformation, Villach, Austria **Johannes Scholz** – Research Studios Austria, Studio iSPACE, Salzburg Austria **André Skupin** – San Diego State University, Department of Geography, San Diego, CA 92182-4493, USA				
Submission Info: (Type, Conference,…)	Short Paper in Proceedings of Workshop "Analysis of Movement Data'14" Workshop at GISciecne 2014	**Published:** (year)	2014	**Pages:**	8
Reference:	**Schabus, S., Scholz, J., and Skupin, A. (2014),** Spatial-temporal Patterns of Production Assets in an Indoor Production Environment. In Proceedings of Workshop "Analysis of Movement Data'14" Workshop at GIScience 2014, Poster Presentation, Vienna, Austria. Web: http://blogs.utexas.edu/amd2014/ [last visited 29-07-2015].				

Short Description of Authors Activities					
Stefan Schabus: (*Candidate*)	▪ Wrote mainly the manuscript ▪ Modelling of data model ▪ Implementation of SOMs	**Johannes Scholz:**	▪ Supported the writing of the manuscript ▪ Managed Revision and Submission	**André Skupin:**	▪ Critical Feedback and Review ▪ Co-Development of Data Model ▪ Input of Self-Organizing Maps

Detailed Description of PhD (*Stefan Schabus*) **- Activities**

- The candidate wrote main parts of the manuscript
  - Johannes Scholz supported the writing – focus on the characterization of the indoor space
  - Andrè Skupin supported with language review and insights of Spatial-Temporal Data mining
  - The structure was developed by all authors
- Developed the data model of the relevant production assets
- Implementation of the Analysis
- Interpretation of the Analysis results supported by André Skupin

Figure 5.1: *Author Activity Description: Spatial-Temporal Patterns of Production Assets in an Indoor Production Environment (Schabus et al., 2014).*

Spatial-temporal Patterns of Production Assets in an Indoor Production Environment

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1. Introduction

Spatial information systems have traditionally been focused on the modelling of outdoor spaces, though spatial phenomena are actually encountered in both outdoor and indoor contexts. In fact, indoor environments play a particularly central role in human activities, and the average person spends approximately 90% of his/her time inside buildings (Jenkins et al. 1992). Conceptual approaches and technical solutions for mapping outdoor spaces tend to be further developed and more sophisticated than indoor applications, exemplified by the ubiquitous availability of satellite technology (GPS) and aerial photography for data collection and positioning tasks (Worboys et al. 2011). Indoor spaces have only recently begun to receive focused attention of research and development efforts, and much work needs to be done to imbue indoor spatial technology with the richness and sophistication that is common place in outdoor spatial information systems.

Industrial manufacturing is – among the application domains – bearing particular potential for indoor spatial modelling. Methodologies originally developed for outdoor phenomena can be adapted in order to improve decision-making in the production process. A stronger role for visualization and an improved consideration of explicit spatial context are among the key aspects of these spatially informed models, including an emergence of location-based services in indoor environments. The current paper specifically focuses on how processes of production assets can be monitored and modelled in an indoor environment.

In order to analyse the patterns of production assets' movements, we employ a high-dimensional conceptualization of production assets in conjunction with use of the self-organizing map (SOM) method, an artificial neural network approach that supports is automatic data analysis (Kohonen 2012). SOMs are typically represented as two-dimensional lattices of neurons, each being connected to other neurons according to specific topological principles. With the help of this low-dimensional grid, high-dimensional patterns can be visually explored (Kohonen 1998, Kohonen et al. 1996). The method has been used to support complex tasks like process analysis, perception of machines, control and communication. The characteristics of the SOM method, including its alternate use as clustering or dimensionality reduction technique (Agarwal and Skupin 2008), suggest its possible use in the movement analysis of production assets. This is explored in some detail in this paper, including an exploration of patterns of quality measurements performed on production assets.

The scientific question of this paper is focusing on the modelling of production assets movements in indoor environment. Additionally, the applicability of SOM to analyse indoor movement patterns of production assets and to detect possible quality issues in the production processes.

The organization of the paper is as follows. Chapter 2 elaborates on the Indoor Production environment under review, followed by a characterization of movement patterns of production assets in a production environment. Additionally, chapter 3 highlights SOM-based analysis spatio-temporal patterns of production assets in relation with quality issues.

2. Characterization of Indoor Production Environment

An indoor production environment has several peculiarities that distinguish it from other production environments and ordinary indoor spaces. This section is based on the work of Geng (2005) and Osswald et al. (2013) and personal experience.

Any semiconductor fabrication is operated in a clean room environment that ensures a low proportion of contaminating particles. Clean room space is expensive to construct and maintain, thus they are designed as compact as possible for the chosen equipment to be placed inside.

Generally, the layout of a production hall differs from classical production environments and ordinary indoor environments. Office or residential buildings' indoor space can be divided into rooms and corridors that are connected by doors. In a semiconductor environment, rooms are hardly present due to the fact that the indoor space is organized in distinguishable corridors with considerable length (see Figure 1). Scholz and Schabus (2014) describe an indoor navigation ontology focusing on the movement of production assets in an indoor environment.

Generally, the production of microchips is a complex process chain (i.e. a sequence of equipment that has to be visited) that involves several hundred different production steps not aligned on a conveyor belt. Hence, the movement processes have a multifaceted structure due to a multitude of different microchip types having different production process chains. In addition, equipment is geographically dispersed over the indoor space. It has to be pointed out, that several pieces of equipment for a certain production step are located in different positions in the production environment with considerable distances between them – as an asset moves several kilometres indoor from first to last production step. Thus, operators handling the production assets have the choice between different machinery to perform a certain production step. Quality issues – like contamination or scratches – arise due to general problems in the clean room environment, any other processes in the vicinity of the production asset or a general problem in the handling of the production assets (e.g. damage during transport).

Managers are interested in understanding where and when quality issues arise, which microchip types and equipment are prone to errors and why quality problems occur, due to the fact that they are an important factor for productivity measures.

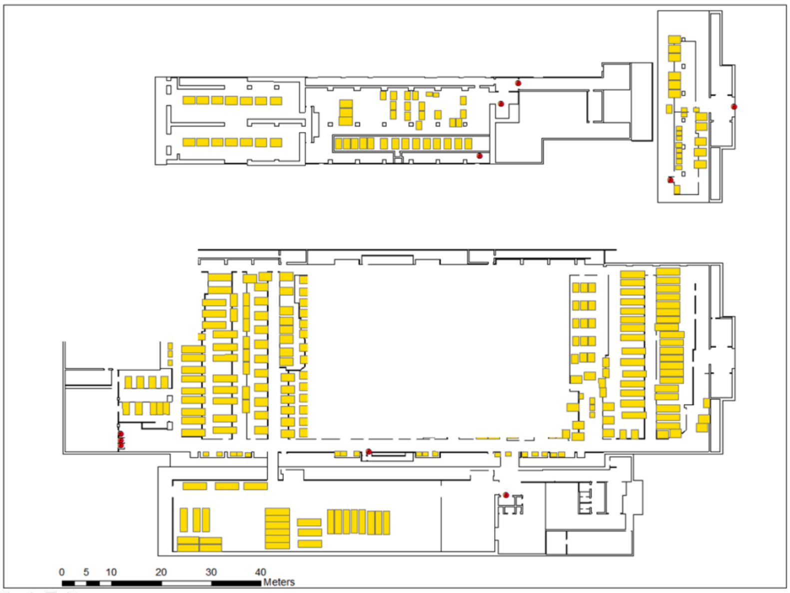


Figure 1. Indoor space layout of the semiconductor production subject of this paper. Equipment is represented by yellow rectangles and transfer points are denoted with red dots. White spaces are included intentionally to disguise the production layout.

3. Analyzing Spatio-temporal Patterns of Production Assets

As mentioned in the last paragraph, analysing spatio-temporal patterns of production asset and quality issues is an important issue for semiconductor production management. This is especially true if the production is not following the rigidity of a traditional conveyor belt approach, but instead occurs in a more dynamic and flexible production environment. It would appear that recent methodologies for analysis of moving object trajectories are of particular relevance in this context (Jeung et al., 2011; Alvares et al., 2007).

To analyse the movement behaviour and quality measures of production line processes a Self-Organizing Map (SOM) algorithm is used. SOMs are artificial neural networks that represent high-dimensional data in a low-dimensional way. Besides they preserve the topological properties (i.e. neighbourhood) of the input space. Basically, visualization techniques used for SOMs are covered by Skupin and Esperbè (2011). The paper describes the SOM itself, the mapping of *n*-dimensional vectors onto SOM as well as the linking of a SOM with other display spaces.

The basis for the approach followed in this paper is a spatio-temporal data model providing information about the movement of production assets as well as information about quality aspects. The approach uses SOM to analyse spatio-temporal movement data and quality measures which are linked to other spaces including the physical space, attribute space and time. Specifically, we link the indoor geography of the production line to the attribute space of various production assets moving through the production line over time.

To understand the general movement of production assets we use the examples depicted in Figure 2. Figure 2 shows examples of production assets processed along a pre-defined sequence of equipment. At each equipment an asset checks in, gets processed and checks out the equipment after the production step is finished. The check-in and check-out processes are recorded with a timestamp. Additional information, namely a start and end time is provided that describe the time when a production asset enters and leaves the production facility. Generally, the processing time of a single production process may vary depending on the equipment used and depending on the asset type (i.e. microchip type). Additionally, the different production steps (i.e. etching vs. implantation) take different amount of time. As the transport from one piece of equipment to the next is done by human operators it is obvious that the time transport time between two subsequent production steps may vary greatly. Thus, if two assets of the same type enter the production line simultaneously, it is very likely that the production is not finished at the same time.

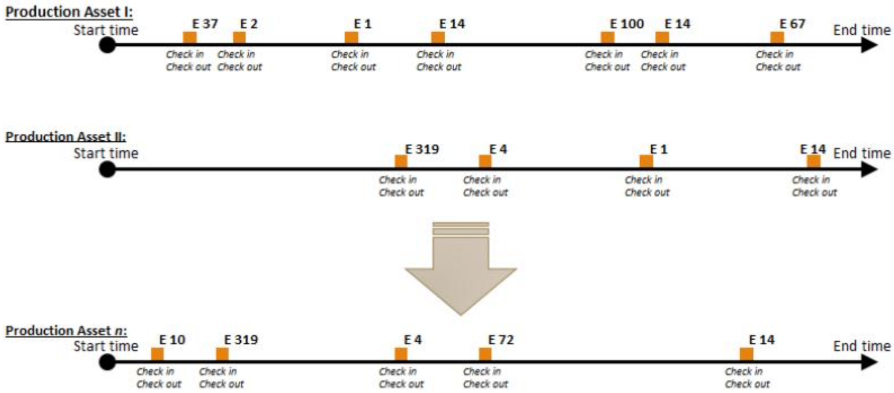
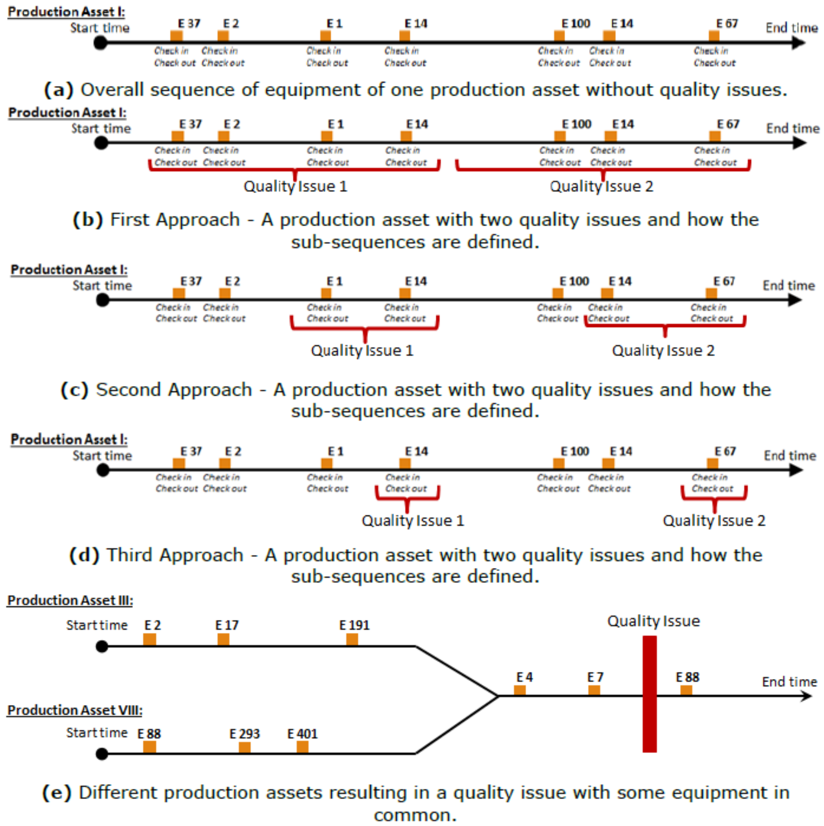


Figure 2. Abstract model of the production asset moving through a sequence of equipment over time (from start to end of the production process).

In order to analyse the quality issues occurring in the production line, we define a quality issue (e.g. contamination) with respect to a sub-sequence of several pieces of equipment. A quality issue is detected after the check-out of a production asset from the equipment. At this stage a number of quality checks are performed – and if one or more values are out of an allowed range, a quality issue is raised. Due to the fact that quality checks are not performed at each equipment, we include the sequence of machines up to the last positive quality check in our sub-sequence under review. This leads to the possibility to identify pieces of equipment that are more likely to be involved in a quality issue. An overview of some possible sub-sequences of quality issues is given in Figure 3.



(a) Overall sequence of equipment of one production asset without quality issues.

(b) First Approach - A production asset with two quality issues and how the sub-sequences are defined.

(c) Second Approach - A production asset with two quality issues and how the sub-sequences are defined.

(d) Third Approach - A production asset with two quality issues and how the sub-sequences are defined.

(e) Different production assets resulting in a quality issue with some equipment in common.

Figure 3. Definition of a quality issue and the corresponding sequence in the production line – i.e. the equipment sequence from the quality issue to the last positive quality check.

In order to test the approach of applying a SOM to indoor production data, historical spatio-temporal movement data and quality issue data of an Austrian semiconductor manufacturer are used that cover one month time period. The spatio-temporal data are migrated into a PostgreSQL/PostGIS database using a data model that reflects their inherent spatial and temporal dimension. In order to train the SOM, we used the SOMatic Training Software, developed at the Department of Geography of San Diego State University. After creating the SOMs we employ the SOMatic Viewer to compare and analyse the component planes. Additionally, a JavaScript-application is developed for the purpose of analyzing physical, attribute space and time accordingly (see Figure 4). After having detected a cluster of quality issues, the physical space can by visualized and analysed over time accordingly (see Figure 5).

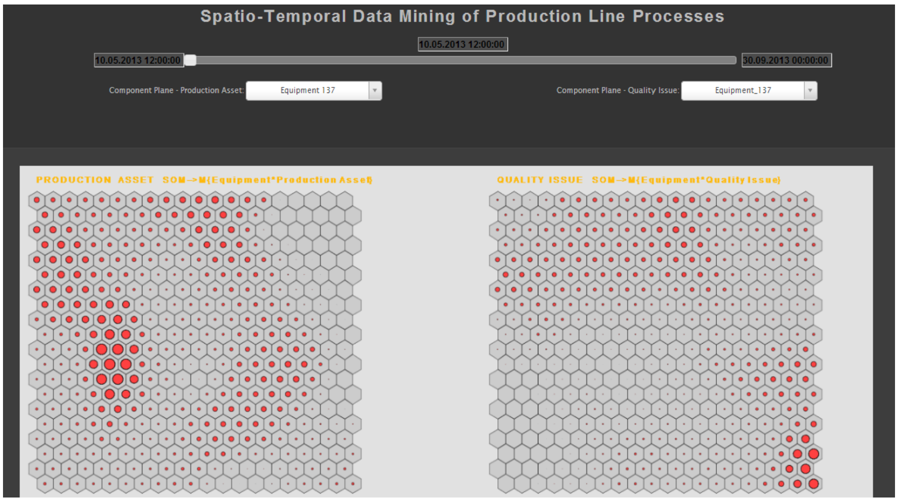


Figure 4. JavaScipt-Application for analysing physical, attribute space in relation to the temporal component by a time slider.

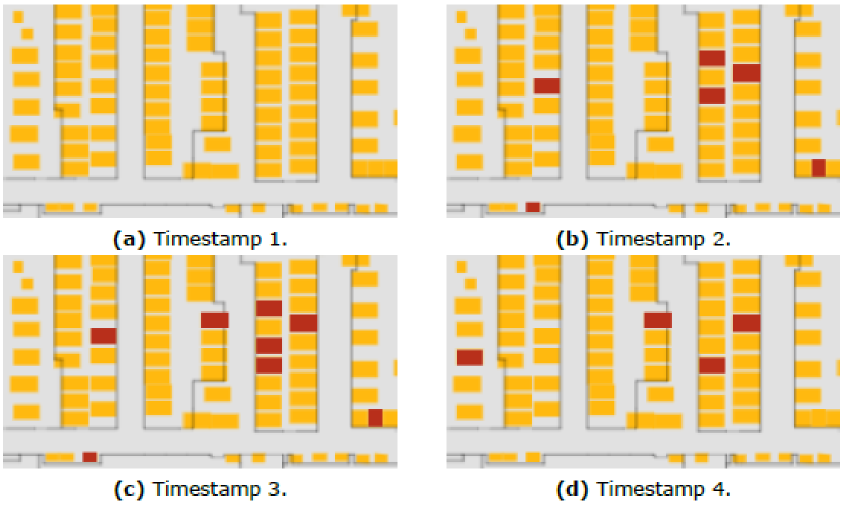


Figure 5. An evolving pattern of quality issues in the physical space over time. Yellow rectangles represent equipment without a quality issue, and red rectangles mark equipment with a recorded quality issue.

The resulting component planes of the SOM with respect to quality issues and the frequency of the equipment offers the opportunity to compare different equipment regarding the similarity of quality issues. Figure 6 shows an example of similar equipment and one corresponding quality issue. Similar neurons occur in both of the selected component planes. Equipment 28 (depicted on the left side of Figure 4) is more frequently used if a quality issues occurs, as darker areas can be identified. Darker areas – in this context – depict more frequently used neurons. In addition, if they occur in several component planes, these neurons occur more likely in a sub-sequence leading to a quality issue.

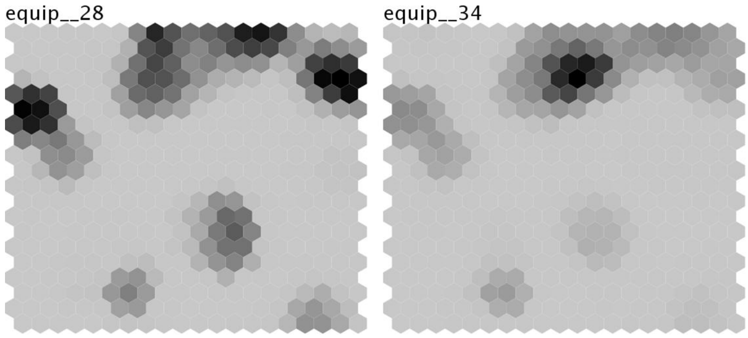


Figure 6. Component planes of the quality issue of similar equipment.

The second example shows quality issues concerning two different pieces of equipment (see Figure 7). The component planes are completely different with respect to the clusters of affected neurons. Equipment 2 has a very limited cluster of affected neurons in the left-bottom corner. Due to the limitation of neurons, the equipment is only appearing rarely in the sequence of a quality issue. Additionally, it is not very likely that it appears in the sub-sequence of a quality issue. Equipment 367 appears in several different sequences of quality issues as there are some distinct and distributed areas. In addition, equipment 367 appears in one larger cluster of quality issue sequences in the right-top corner more frequently than in the other clusters. This shows that equipment 367 appears different sub-sequences that lead to a quality issue. There is a higher likelihood that this equipment 367 leads to a quality issue than equipment 2.

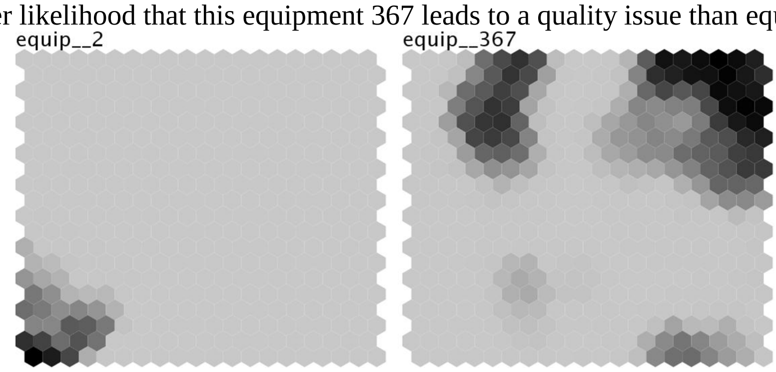


Figure 7. Component planes of the quality issue of different equipment.

4. Conclusion and Discussion

This article elaborates on the analysis of spatial-temporal patterns in a production environment. Key elements include the need for improved understanding of the movement of production assets and the analysis of spatial-temporal patterns of quality issues encountered along the production line. To that end, the movement of production assets is conceptualized as the sequence of equipment pieces encountered by each asset. This leads to the modelling and definition of a quality issue which is analysed using the spatial-temporal data mining method SOM. The creation of a SOM provides the comparison of component planes per equipment giving an overview which equipment occurs more or less likely in a quality issue. This leads to new insights into historical movement data, which might give insight in the production environment and is likely to support decision making.

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Chapter 6

A Space in a Space: Connecting Indoor and Outdoor Geography

For Geographic Information Science and Technology (GIS&T), the connectivity between outdoor and indoor geography is essentially to re-use application and tools. Conceptual data models of connectivity types are established. The focus is either on the co-existence of spaces or the a space in a space approach. The co-existence describes spaces that are next to each other with the possibility to change from each space to another one. The a space in a space approach is conducted if a space is completely encapsulated by one space. Figure 6.1 presents the author activities (Schabus et al., 2015).

<table>
<tr><td>Title:</td><td colspan="7">A Space in a Space: Connecting Indoor and Outdoor Geography</td></tr>
<tr><td>Authors:</td><td colspan="7">Stefan Schabus – Infineon Technologies Austria AG, Villach Austria
Johannes Scholz – Graz University of Technology, Institute of Geodesy, Research Group Geoinformation, Graz, Austria
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<tr><td>Submission Info:
(Type, Conference,…)</td><td colspan="3">Short Paper In 18th AGILE International Conference on Geographic Information Science, Lisbon 2015 (peer reviewed)</td><td>Published:
(year)</td><td>2015</td><td>Pages:</td><td>5</td></tr>
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<tr><td colspan="8">Short Description of Authors Activities</td></tr>
<tr><td>Stefan Schabus:
(Candidate)</td><td>▪ Wrote mainly the manuscript together with Johannes Scholz
▪ Modelling of the connectivity between spaces</td><td>Johannes Scholz:</td><td>▪ Wrote the manuscript together with Stefan Schabus
▪ Managed the submission process</td><td>Thomas J. Lampolts-hammer:</td><td colspan="3">▪ Critical reviewed the written paper
▪ Discussion of the conceptual model</td></tr>
<tr><td colspan="8">Detailed Description of PhD (Stefan Schabus) - Activities</td></tr>
<tr><td colspan="8">▪ The candidate was the main author of this publication
    ▪ Johannes Scholz supported the writing of the manuscript and provided feedback
▪ Together with Johannes Scholz also the structure and content of the manuscript is set up
▪ Modelling and Conceptualization of Indoor-/Outdoor Connections
    ▪ Development of abstract and real-world examples
▪ Management of the internal publication release of the production company</td></tr>
</table>

Figure 6.1: *Author Activity Description: A Space in a Space - Connecting Indoor and Outdoor Geography (Schabus et al., 2015).*

A Space in a Space:
Connecting Indoor and Outdoor Geography

Abstract

Spatial phenomena can be encountered in outdoor and indoor geography-related contexts: The description and analysis of indoor environments is an important factor as research on indoor geography has recently gained certain momentum. To imbue a clear understanding of indoor space, the definition is a crucial issue as the concept of indoor geography is heavily context-based. Therefore, ontologies have the capability to describe such a context-specific indoor space in a semantic manner. The aim of this work is to analyse the occurrence and the accessibility of different indoor spaces and the connection to the outdoor space. Therefore the paper highlights the possible connections between indoor and indoor space and the connections between outdoor and indoor space. A specific focus is given to indoor to indoor space connections, and the fact that indoor spaces can be separated from each other. The analysis will result in models highlighting the connectivity of a common outdoor space and indoor space where the indoor space is connected to another "nested" indoor space not accessible from outdoor. Nevertheless, the connection between each defined space has to be a consistent basis for applications such as navigation or visualization purposes with specific focus to indoor production environments.

Keywords: Indoor Geography, Indoor Space, Ontology, Indoor Production Environment

1 Introduction

Recent years showed higher efforts in outdoor geography-related research than for indoor geography. This is due to the fact that outdoor geography already possesses a high level of structured methods and applications. However, indoor geography-related research is attaining more attention during recent years, as an average person spends almost the entire day inside of buildings [1, 2]. Additionally, the overall size of buildings is increasing, comprising their complexity as well, which in return raises the need for indoor location-based services [3]. Buildings can feature a varying degree of complexity, different sizes, and fulfill different functionalities. Indoor geography-related research has the high potential to evolve transport simulations, the analysis of indoor geography, and its utilization regarding navigation purposes. The availability of ubiquitous positioning systems such as the global positioning system (GPS) and aerial imagery in the outdoor geography is highlighted by Worboys [1]. Due to the emerging interest of indoor geography-related research also location-based services and applications intend to make the step from outdoor to indoor.

Indoor geography-related research depends on the application domain as well. One possible application domain can be found in indoor navigation within complex buildings. For instance, indoor spatial modelling can be of high potential for indoor production environments. Scholz & Schabus [4] developed an indoor navigation ontology for indoor production environments, including arising navigational tasks. This ontology describes how indoor geography can be applied to a manufacturing site and sets a proper basis for spatial analysis in an indoor environment. Jonietz and Timpf [5] describe an approach where affordances of spatial artefacts are used for modelling routing, which can be used as an alternative approach for spatial analyses and navigation.

Schabus et al. [6] carried out a spatial-temporal analysis by assessing historical data recorded during production processes in an indoor production environment. They employed self-organizing maps (SOMs) in combination with a conceptual modelling approach of movements of production assets. SOMs are one type of artificial neural network algorithms that supports automatic data analysis while providing a visual exploration [7], which is achieved by dimensionality reduction and clustering [8].

In general, ontologies are a powerful methodology to understand complex behavior as it provides a simplified representation [9]. Ontologies have the ability to be a domain or application-specific symbol to represent knowledge throughout different groups and scientific fields [10].

This paper discusses the connection of different indoor geographies under consideration of related outdoor geographical aspects. In particular, indoor spaces are analysed by the example of an indoor geography of a production environment with special peculiarities and affordances.

The remainder of the paper is organized as follows: Section 2 elaborates on a possible characterization of indoor space including an indoor production environment followed by an indoor navigation ontology and a comparison of outdoor-/ indoor geography. Section 3 focuses on the modelling of possible connections between indoor-/indoor spaces and indoor-/outdoor spaces. Finally, section 4 closes with a conclusion and potential research outlooks.

2 Characterization of Indoor Spaces

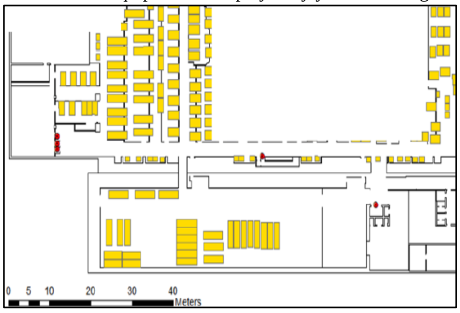
The proper characterization of indoor space is essential for an accurate modelling and understanding of indoor space. However, the modelling of indoor structures is not straight forward as it is strongly intertwined with the associated application field of the building itself [11, 12]. To give an example of the complexity at hand, section 2.1 discusses the arising challenges of an indoor production environment. Afterwards, section 2.2 discusses the concept of nodes used for the transfer and access in indoor spaces.

2.1 Indoor Production Environments

An indoor production environment is a challenging indoor space due to its high complexity. One example of a production line is represented by a semi-conductor fab. This indoor production environment features a high variability of production assets with different degrees of completion present at the same point in time. Additionally, the processing time of production assets varies from several days to a couple of weeks and each production asset requires a high number of production steps from beginning until the end. Each production step may necessitate capacity of several equipment pieces, which can be geographically distributed over the entire indoor production environment [4]. Additionally, aspects of cognition of indoor spaces and indoor landmarks have to be taken into account [13]. This circumstance is specifically challenging, as indoor production environment landmarks are difficult to define due to their changing characteristics over time. One way to tackle these issues is found within graph-based methods. This approach enables an affordance-based navigation similar to Jonietz & Timpf [5], as nodes could serve as bridge between indoor spaces and outdoor space.

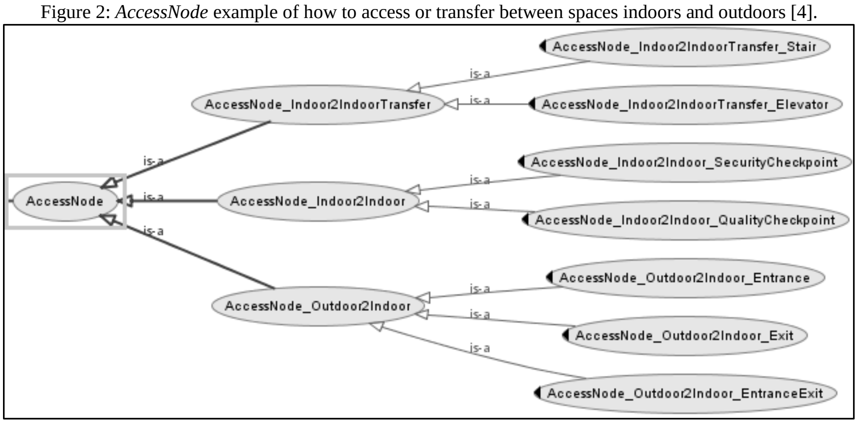
Due to personal experience, the work of Geng [14] and Osswald et al. [15], it can be stated that the production of microchips is a complex process chain, which has to be carried out under special cleanroom restrictions. As cleanroom space is expensive to construct and maintain production halls cannot be extended too easy. Hence, cleanroom space is a limited property. To justify the complex production process, production assets move several kilometers within the indoor environment, while the movement exhibits a multi-faceted structure due to different microchip types, which have to be transported. Figure 1 shows such an indoor environment.

Figure 1: Layout of the Indoor space of production environment - equipment is displayed by yellow rectangles.



The layout of a production hall is different than classical production environments, due to the cleanroom conditions and restrictions. Furthermore, it differs from public office buildings or residential buildings as, e.g. rooms are hardly present. Fig. 1 depicts an extract of such an indoor production environment, which is separated into long corridors with fairly distributed equipment, which can be identified by yellow polygons.

Figure 2: *AccessNode* example of how to access or transfer between spaces indoors and outdoors [4].



2.2 Nodes as a Way to Access Indoor Space

As mentioned in section 2.1, graph-based methods are a promising way to model indoor space and to manage transfers between spaces in general. Such an approach is applied by Scholz & Schabus [4] as they employed a so-called *AccessNode* to represent either transfer between building levels, indoor spaces, or even between outdoor and indoor spaces and vice versa. Figure 2 represents the corresponding class hierarchy associated to the *AccessNode*.

Basically, the class *AccessNode* is split into three sub-classes, namely “Outdoor2Indoor”, “Indoor2IndoorTransfer” and “Indoor2Indoor”. The detail description is as follows [4]:

- "AccessNode_Indoor2IndoorTransfer" represents the connection within the same indoor space, thus it is connecting for instance different building levels. The sub-classes are "Elevator" and "Stair", whereas the transport over a stair is used for the transfer between different building levels in the same indoor space with special restrictions. These restrictions have to be defined as it is dangerous to transport valuable production assets over a stair. In order to change the building level with a production asset the elevator has to be considered including a time constraint.
- "AccessNode_Indoor2Indoor" enables a transfer between different indoor spaces. The sub-classes are Quality-Checkpoint and Security-Checkpoint". A quality check can be an example for an air lock, as in a semiconductor production environment special air conditions have to be considered. The security checkpoint highlights access restrictions.
- "AccessNode_Outdoor2Indoor" represents the connection from outdoor geography into the indoor environment. Therefore, the subclasses "Entrance", "Exit" and "EntranceExit" are necessary. The "Entrance" sub-class enables the movement from outdoor into the indoor space. The "Exit" defines designated doors for leaving a production environment such as a cleanroom. The "EntranceExit" both ways from outdoor to indoor and vice versa.

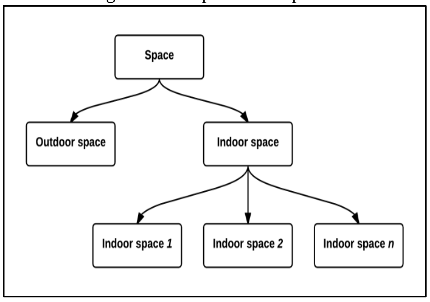
This example of a defined node demonstrates a transfer opportunity between different indoor and outdoor spaces. Therefore, a graph is a good starting point as it is also enabling navigation within a building, and especially in a production environment. The graph structure can be modified and adjusted to create access and transfer points between spaces.

2.3 Comparison of Spaces

In order to be able to compare spaces accordingly, a tree is set up listing the outdoor space and indoor space relationships. Figure 3 illustrates the comparison of spaces. In a first step space is split up into outdoor space and indoor space – based on the same level of detail similar to Yang & Worboys [16]. In this abstract example the outdoor space represents the world outside a building. At the same level of detail the "opposite" of the outdoor space is the indoor space, which represents the world inside a building.

If we go one step further, indoor space can be subdivided into different indoor spaces. Therefore, figure 3 shows that the indoor space is divided into indoor space 1, indoor space 2 and the opportunity for other indoor spaces. Indoor space 1 can be an example for a public building or a residential building. Indoor space 2 can be a production environment with constraints regarding air quality and thus in installed air lock to enter the building. Another opportunity for an indoor space could be a separate environment where security clothes are necessary in case of chemicals. Additionally, a fine grained subdivision of an indoor space could take place, which is described in section 3.2. For spatial analysis this would require to look at indoor spaces with different scales depending on the question to be answered (i.e. is a person inside a building vs. inside a room?)

Figure 3: Comparison of spaces.



3 Modelling of Indoor-/Outdoor Connections

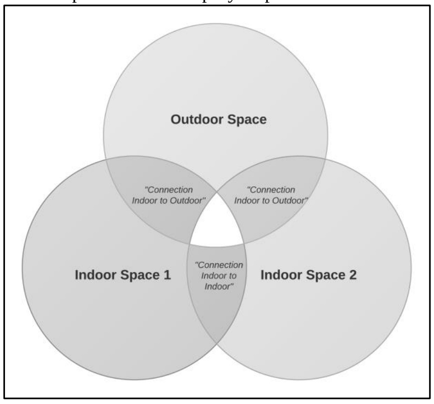
Modelling of indoor space or outdoor space is essential for the development of new applications. It is a challenge to develop an application connecting several spaces as this process requires considerable modelling effort to represent reality in an accurate manner. This section describes on one hand the opportunity of co-existence of spaces and on the other hand a clear separation of spaces defined here as a *space in a space.*

3.1 Co-Existence of Spaces

There is a co-existence of spaces next to each other. This implies that all spaces are connected via some type of node (and edge) or, in real world, an entrance of a building connecting outdoor space and indoor space. An abstract model of this co-existence is illustrated in Fig. 4 with a modified Venn diagram. This diagram points out three different spaces, which are i) *the outdoor space*, ii) *indoor space 1*, and iii) *an indoor space 2*. The main essence is the possibility to establish connections between each space separately, but not to connect all spaces into one.

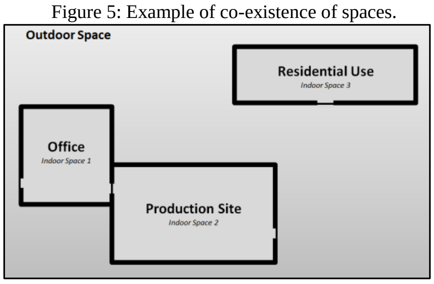
Figure 4 clearly shows that there exists a connection from *the outdoor space* to *indoor space 1* and to *indoor space 2*. However, there is no way to connect *the outdoor space*, *indoor space 1*, and *indoor space 2* all three in one way if the boundaries of each space are crisp. Then it is only possible to transit from one space to another space, step-by-step wise.

Figure 4: Modified Venn-diagram showing the co-existence of spaces and the step-by-step connection.



A real-world instance of the concept is depicted in Fig. 5. The example describes the co-existence of space. The example shows that the outdoor geography wraps-around the indoor spaces.

Figure 5: Example of co-existence of spaces.

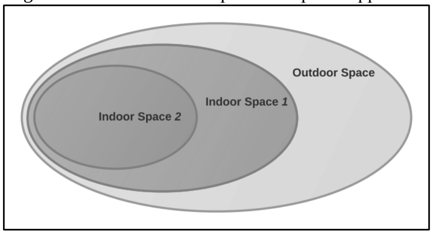


The indoor spaces are separated into one office building as *indoor space 1*, a production site as *indoor space 2* and a building for residential use as *indoor space 3*. The office and the production site are building but separate indoor spaces due to security reasons. For instance, not every employee of the production site is allowed to enter the office building. Indoor space 3 is only accessible for residents.

3.2 A Space in a Space

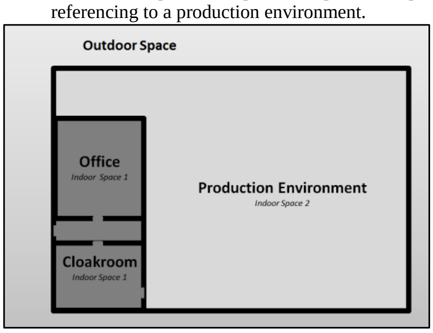
To model the characteristics of disjoint spaces, the "*a space in a space"* concept is introduced. This concept enables the modeling of special conditions, for example, as imposed by an indoor production environment. Figure 6 depicts the existence of a space in a space. The outdoor space wraps around all indoor spaces as does is in real world. Within *the outdoor space, indoor space 1* is located. *Indoor space 1* completely contains another *indoor space 2*. This *indoor space 2* is disjoint with the *outdoor geography* and cannot be accessed directly from outdoors.

Figure 6: Model of the "A space in a space" approach.



To illustrate the "*space in space*" concept, the reader is referred to Fig. 7. Again, the example of an indoor production facility is chosen. One building includes two separate indoor spaces. The production hall itself contains offices, a cloakroom, and the production environment.

Figure 7: Practical example of the space in a space concept by referencing to a production environment.



The production environment is secured by an air lock to establish special cleanroom conditions as described in section 2.1. From the production environment, with cleanroom conditions, it is not possible to get directly into the outdoor space. In that respect, the production environment and the outdoor space are two disjoint spaces. However, the cloakroom in indoor space 1 is accessible via the outdoor geography and the production environment (indoor space 2) is accessible via an airlock located between the cloakroom (indoor space 1) and the production space (indoor space 2).

This example points out that spaces can be very closely located but still disjoint. Both indoor spaces are separated from the outdoor space only by a wall. In contrary to indoor space 2, indoor space 1 is accessible from outdoors. The conditions behind the wall are the only reason for enabling the access only via an air lock and thus limiting the access to indoor space 2 – which is visualized in figure 7. Additionally, indoor spaces can also change over time due to the need of a higher level of air quality for new products or new production devices that require a reshaping of the indoor space.

4 Discussion and Conclusion

The paper elaborates on the connectivity of indoor and outdoor spaces, which includes mainly the connection of outdoor and indoor space and indoor to indoor space. On one hand, spaces, both outdoor and indoor, are in a co-existence state, meaning that the spaces are connected. On the other hand, we introduced a "*space in a space*" model, where spaces may be related while other spaces are disjoint. An example is given that highlights an indoor production environment with specific conditions and limited accessibility.

Future research directions include the investigation of possible connections between outdoor and indoor spaces, as well as any other possible connections of indoor spaces. Both aspects may be investigated with respect to space and time (e.g. how to model changes in indoor spaces), scale and/or fuzzy boundaries. This paper can also contribute to topics that seem thematically further away such as spatial-temporal analysis of indoor movements, simulation of movement behavior as well as an investigation of necessities and peculiarities of spatial-temporal analysis methods for indoor space.

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Chapter 7

Geographic Information Science and Technology as Key Approach to unveil the Potential of Industry 4.0

The potential of applications based on GIS&T applied in smart manufacturing is covered within this chapter. The included publication presents a modelled indoor space of a production environment and the resulting GIS-based visualization. This includes data analysis based on location and time where and when production processes or transportation processes occur. Figure 7.1 introduces the author activities and responsibilities (Schabus and Scholz, 2015).

<table>
<tr><td>Title:</td><td colspan="5">Geographic Information Science and Technology as Key approach to unveil the potential of Industry 4.0:
How Location and Time can support Smart Manufacturing</td></tr>
<tr><td>Authors:</td><td colspan="5">Stefan Schabus – Infineon Technologies Austria AG, Villach Austria
Johannes Scholz – Graz University of Technology, Institute of Geodesy, Research Group Geoinformation, Graz, Austria</td></tr>
<tr><td>Submission Info:
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(year)</td><td>2015</td><td>Pages:</td><td>8</td></tr>
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<tr><td colspan="6">Short Description of Authors Activities</td></tr>
<tr><td>Stefan Schabus:
(Candidate)</td><td>▪ Mainly wrote the manuscript, supported by Johannes Scholz
▪ Responsible for Revision and author correspondence</td><td>Johannes Scholz:</td><td colspan="3">▪ Supported the candidate writing the manuscript
  ▪ Main focus was on chapter 2 – ‘Indoor Geography, Outdoor geography and the temporal Dimension’
▪ Critical Review and Feedback about content</td></tr>
<tr><td colspan="6">Detailed Description of PhD (Stefan Schabus) - Activities</td></tr>
<tr><td colspan="6">▪ The candidate wrote main parts of the manuscript, supported with critical reviews and input of Johannes Scholz
  ▪ Forehand, the structure was developed by both authors

▪ Modelling and implementation was executed by the Candidate
  ▪ Approach to unveil potential of Industry 4.0

▪ Management of internal release processes of the production company and external release processes of the publisher</td></tr>
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Figure 7.1: *Author Activities: Geographic Information Science and technology as Key Approach to unveil the Potential of Industry 4.0 (Schabus and Scholz, 2015).*

Geographic Information Science and Technology as key approach to unveil the potential of Industry 4.0

How Location and Time can support Smart Manufacturing

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Abstract: Productivity of manufacturing processes in Europe is a key issue. Therefore, smart manufacturing and Industry 4.0 are terms that subsume innovative ways to digitally support manufacturing. Due to the fact, that geography is currently making the step from outdoor to indoor space, the approach presented here utilizes Geographical Information Science applied to smart manufacturing. The objective of the paper is to model an indoor space of a production environment and to apply Geographic Information Science methods. In detail, movement data and quality measurements are visualized and analysed using spatial-temporal analysis techniques to compare movement and transport behaviours. Artificial neural network algorithms can support the structured analysis of (spatial) Big Data stored in manufacturing companies. In this article, the basis for a) GIS-based visualization and b) data analysis with self-learning algorithms, are the location and time when and where manufacturing processes happen. The results show that Geographic Information Science and Technology can substantially contribute to smart manufacturing, based on two examples: data analysis with Self Organizing Maps for human visual exploration of historically recorded data and an indoor navigation ontology for the modelling of indoor production environments and autonomous routing of production assets.

1 INTRODUCTION

Geographic Information Science (GISc) is an approach to describe, model, analyse and visualize spatial phenomena as well as spatial processes representing measurements. These representations are used to identify the emphasis of spatial themes and different entities including their relationships between locations and features linked to locations (Chrisman et al. 1989). In addition, Goodchild (1991) sets the emphasis of a Geographic Information System (GIS) to the handling and usage of spatial data. Therefore, an understanding of natural phenomena coupled with scientific methods and knowledge is necessary in order to model spatial real-world phenomena accordingly (Goodchild, 1991). Thus, a GIS is a framework to analyse spatial information linked with attributes to generate new results and insights out of spatial data.

Recently, higher efforts have been made in outdoor geography than in indoor geography due to the fact that already a high number of applications and structured methods exists (Giudice et al. 2010; Worboys, 2012). A comprehensive task is the positioning both in indoor and outdoor environments (Li et al., 2008). There are different challenges of the positioning problem. Indoors, there are limitations of the rooms' size, the building and the indoor environment in general. In contrary, outdoor geography requires a regional or global coverage (Mautz, 2008).

Indoor Geography related research is gaining increasing interest.The variety of complex buildings and the application specific development is increasing the need for location based services indoor (Goetz, 2012). In order to support complex production processes Scholz and Schabus (2014) developed an indoor navigation ontology that describes the indoor production environment with all relevant features including an autonomous navigation for a production environment. According to Janowicz (2008) and Gruber (1995), ontologies are a specification of a conceptualization and are able to model complex behavior as simplified representations. Such spatially enhanced models include the ability to support the analysis of spatial patterns. A movement behavior model has to be developed accordingly which can be used to create Self-Organizing Maps (SOM). SOMs are one type of artificial neural network algorithm (Kohonen, 2013) to analyse attributive data over time.

For a manufacturing site, the productivity and efficiency is a crucial issue. Therefore, smart manufacturing is a new research field as it is strategically important for the industrial sector as it facilitates the competitiveness of a manufacturing site (Davis et al. 2012). Additionally, companies are collecting huge amounts of spatial-temporal data, such as transport movement data, which could be the basis for spatial-temporal data mining e.g. by visualizing maps to enable intelligent pattern recognition. This is useful as humans can identify visual patterns easily (Compieta et al. 2007). Finally, optimization of production processes depends on allocation and sequencing of processes and assets. This unveils the potential to increase the productivity and efficiency going hand in hand with cost-savings and increased performace, which could be one interesting research field for indoor geography and GIS (Nyström, 2006).

The scientific question in this paper can be summarized as "*Can GIS, applied in indoor space and in indoor production line environments, help to understand and optimize production processes*". Thus, we focus on supporting Industry 4.0 with spatial and spatial-temporal analysis to gain added value out of big data using visual analytics.

The paper is organized as follows. Chapter 2 deals with indoor and outdoor geography and the temporal dimension of the production processes. Chapter 3 characterizes the variability of different types of indoor spaces and the indoor space of a production environment including it's specific pecularities. Chapter 4 highlights an approach to visualize and analyze quality measurements and transportation behavior followed by a conclusion and a future research directions.

2 INDOOR GEOGRAPHY, OUTDOOR GEOGRAPHY AND THE TEMPORAL DIMENSION

Geographic Information Systems and Technology are intensively used in outdoor contexts. Thus the theory, methodologies and technologies are well established (Giudice et al. 2010). In contrast, GIS for the indoor context, which is subject of this paper, is rather weakly developed (Worboys, 2012). Nevertheless, the first papers on modeling indoor space and indoor wayfinding were published by Raubal and Worboys (1999) and Raubal (2001). The latter uses an airport as indoor environment and describes an agent-based indoor wayfinding simulation. The term GIS, as used in this paper, describes a computer system to analyze, store, manipulate, analyze and visualize spatial data accordingly (e.g. Longley et al., 2011). Hence, any GIS – with appropriate data – is able to answer the three basic questions:

- *What* happended?
- *Where* did a phenomenon happen?
- *When* did a phenomenon happen?

These questions are valid for any appliation area indoor and outdoor. Also for mobile GIS applications, like apps on a mobile device, a context awareness, in terms of location and time, is inevitable. In GISc, such context-aware services that are consumed by mobile devices are called Location-based Services (e.g. Küpper, 2005).

Classical spatial analysis algorithms are e.g. summarized in De Smith et al. (2007). A prerequisite for spatial analysis is an abstract modeling of the universe of discourse. Therefore a set of basic spatial primitives – point, line, polygon – is utilized that helps to model and abstract reality accordingly. Based on these spatial primitives, any existing spatial relation of the objects can be analyzed. The power of spatial analysis is based on linkages and relationships of locations. Hence, relative positions are more important than absolute ones. Examples of topological relations are adjacency, connectivity, and containment, while non-topological relations are e.g. neighborhood or distance.

In order to represent and model dynamic situations in a GIS one needs to integrate the temporal dimension. Hence, space has to be coupled with time, with the basic assumption that one object can only occupy a distinct part of space at a specific point in time. To describe spatial and temporal processes Hägerstrand (1970) developed an approach named *Time Geography*. There movements of objects are modeled as paths in a 3D-cube with respect to space (i.e. latitude and longitude) and time (see Figure 1). The representation of space and time in a database is basically done with two approaches: discrete vs. continuous (Peuquet, 2001). The discrete approach is comparable to a limited set of time slices with the spatial entities as main elements. The continuous approach favours a space and time representation, where the spatial objects are denoted as attributes attached in space-time.

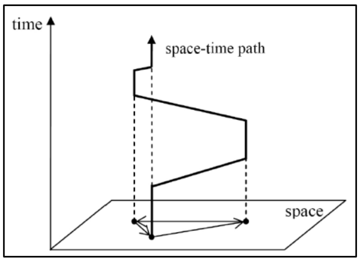

Figure 1: Time and Geography (Graphic from Yu (2006))

Summarizing, GISc seems like a valuable approach to model, analyze and visualize spatial-temporal production relevant data. Especially, due to the capability of any GIS, to analyze data in terms of space and time, it can be helpful to gain new insights in production relevant data.

3 CHARACTERIZATION OF INDOOR SPACE

To characterize indoor space in general, certain effort is needed to generate accurate and consistent models. Due to the high complexity of indoor structures and the context based linkage to the buildings' field of application the characterization is not as straight forward as in outdoor geography (Ascraft, 2008; Meijers et al. 2005). To address the topic of indoor spaces and their characterization, the variability of such indoor spaces is described in section 3.1. In advance, section 3.2 outlines an indoor production environment of a manufacturing site, which results in an indoor navigation ontology for production assets in section 3.3.

3.1 Variability of Indoor Spaces

There is a high variability of indoor spaces. In addition to outdoor geography, indoor geography is much more complex as it is context based (Ascraft, 2008; Meijers et al. 2005). An important topic for the indoor geography is the positioning, as an exact and accurate position is the basis for various upcoming applications (Barnes et al., 2003). According to Mautz (2008), the main difference between outdoor and indoor is the different focus of the positioning approach regionally or globally. Therefore, indoor positioning solutions focus on context-aware-services and on the location of e.g. a person or production assets (Xiang et al., 2004; Al Nuaimi and Kamel, 2011).

3.2 Indoor Space of a Production Environment

The sophisticated arrangement of the indoor space and the peculiarities of the production context require high modelling effort. This section is based on the work of Geng (2005), Osswald et al. (2013), Scholz and Schabus (2014) and personal experience.

Pre-requisites of an indoor production environment are, for example, the clean room environment of a semiconductor fabrication, which has to be built in a very compact way as the construction is very cost-intensive and hard to maintain (Schabus et al. 2014). However, the layout of a production differs from classical production halls using a conveyor belt metaphor as well as from an ordinary indoor environment. According to Schabus et al. (2014), buildings with a context of e.g. residential use are mainly separated into rooms and corridors which can be connected by doors. In addition, a production environment differs through distinguishable corridors with a substantial length and different types of doors such as sliding doors or doors going in one direction, in e.g. an air lock.

In general, the production of a microchip is a complex sequence of equipment which is the context of the indoor production environment of a semiconductor fab. This sequence considers several hundred different production steps which have to be involved and are not aligned along a conveyor belt to keep the flexibility. The flexibility is essential as there is a high number of production assets present at the same time which are also linked to different sequences of production steps and a varying level of completion. Hence, the overall processing time is between several days up to a couple of weeks. To imbue the flexibility, the equipment is also distributed geographically throughout the production hall and different equipment can carry out the same production steps.

To summarize these peculiarities of an indoor production environment, figure 2 highlights the eight main factors - affordances and restrictions - influencing the characterization of the indoor production environment by considering the production assets' point of view. These context based main factors are "*a high number of production assets*", "*several hundred production steps*", "*executable production steps on several tools*", "*geographically distributed equipment*", "*processing* *time and quality depends on equipment*", "*overall processing time*", "*production artefacts from several days to weeks*" and "*different degrees of completion*".

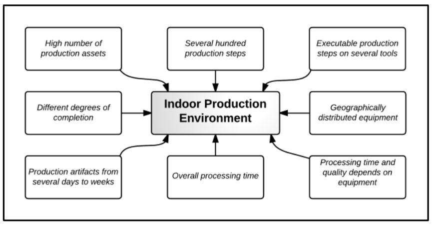

Figure 2: Context-based factors for the indoor production environment in the production assets' point of view.

The indoor production environment of a semiconductor manufacturing site is often separated into corridors with a significant length which is depicted in figure 3. Generally, production assets are moving several kilometres within the production environment. This highlights the potential for decision support present within the indoor geography, as managers would like to know where and when issues arise concerning production processes. Figure 3 highlights the equipment visualized as standardized yellow rectangles and red nodes for the accessing and transferring within/between indoor spaces and outdoors.

To sum up, the indoor geography of a production line environment is a complex environment, due to the specific context of the production. The characterization imbues many factors defining the indoor production environment in detail.

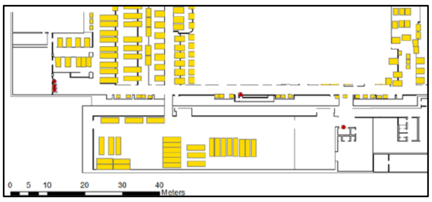

Figure 3: Indoor geography of a production environment using white spaces to hide the exact layout and standardized polygons for visualization purposes.

3.3 Indoor Navigation Ontology for Production Assets

Scholz and Schabus (2014) developed an indoor navigation ontology for production assets in a production environment. Their ontology supports an autonomous navigation in the indoor environment applied with an affordance-based approach.

The navigation ontology is based on eight main entities visualized in figure 4. In general, figure 4 depicts an adapted version of the indoor navigation ontology by Scholz and Schabus (2014). The navigation elements are the moving production asset as "*NavigationAgent*"; "*NavigationEvent*" as start, end or any turn; "*NavigationStructure*" as generic entities for the route calculation.

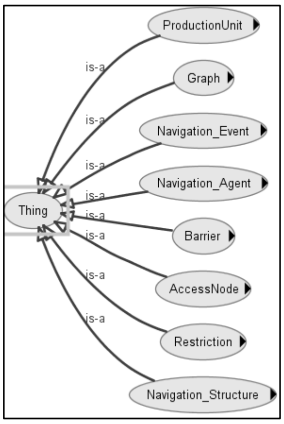

Figure 4: Modified and adapted main elements of the navigation ontology by Scholz and Schabus (2014).

Further elements describing the indoor geography are the "*ProductionUnit*" as facilities and processing units; the "*Graph*" summing up edges and nodes; the "*Barriers*" limiting the movement; "AccessNode" establishing the accessibility or traversing between spaces; the "*Restriction*" to specify affordances.

To sum up, Scholz and Schabus (2014) developed an indoor navigation ontology describing the indoor space and navigation elements. By combining both parts, they successfully established an autonomous indoor navigation approach for a production line.

4 VISUALIZATION AND ANALYSIS OF TRANSPORT AND QUALITY

The visualization and analysis of transport and quality data is the result of a new approach to unveil the potential of smart manufacturing or Industry 4.0

using GISc and technologies. Therefore, geo-visual analytics, map generation, spatial-temporal data mining, trajectory pattern mining and artificial neural network algorithms such as SOMs are used.

Geo-visual analytics and map generation enhance the ability to generate and gain new knowledge out of large datasets of spatial-temporal data. Potential use cases of such visualizations can be incorporated into the optimization of transport-/movement behaviour or the analysis of quality hot spots. Spatial-temporal data mining can be implemented by SOMs as they are one type of artificial neural network algorithm (Kohonen, 2013). SOMs visualize data and set up the basis for visual data mining. Kohonen (1998) implies that SOMs are usable to solve complex tasks like process analysis, perception of machines and control communications. Additionally, Skupin (2010) describes the TRI-space approach linking the geographic space, temporal space and the attributive space.

The topics in this section address an approach for the visualization in section 4.1 followed by an example how the transport-/movement behaviour could be visualized in section 4.2. Additionally, section 4.3 adds the analysis part of the transport-/movement behaviour and quality measurements.

4.1 Approach to unveil the Potential of Visualization and Analysis

A general approach for smart manufacturing under consideration of GIS starts with the modelling and analysis of the base data. Therefore, use cases consider questions about what is temporal or spatial information. Temporal information involves e.g. the duration of something or the timestamp of an event occurrence. Spatial information considers questions such as where was something; what is the shortest path. Defined use cases together with the indoor ontology lead to a spatial-temporal data model, which can serve as general "*data warehouse*" within a company. The additional spatial component of the database enables further queries.

Figure 5 illustrates possible existing systems within a company. It is briefly depicted how a funnel aggregates the data warehouse combining distributed databases, AutoCAD data used for planning purposes and a static viewer of the manufacturing site. This leads to an aggregation and finally to a company-wide GIS. This shows that necessary data sources are available, but have to be integrated and harmonized to unveil their full potential. Thus, a GIS based on one general data warehouse has the potential to unveil the potential of Industry 4.0.

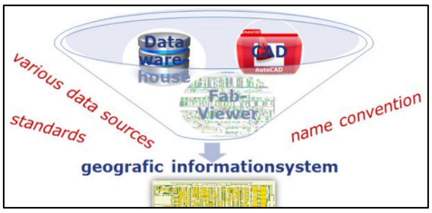

Figure 5: Aggregation of possible existing systems to set up a system building the basis for a GIS.

4.2 Visualization of Transport Behaviour

The visualization of the movement-/transport behaviour is the first step towards the optimization potential within the transport of production assets. Basically, the transport is visualized as the movement itself is recorded and stored as historic information within a data warehouse described in section 4.1. Based on recorded timestamps of the movement and the linking to a specific production asset an approximation of the movement or transport is recovered.

To establish the visualization of movements through a production line, a network structure is necessary. In order to represent possible walking ways or transport corridors within a network accurately, a graph based network is developed. Such a graph based network exists of edges and nodes combining equipment in the production line and facilities which have to be included in a routing approach – which are defined in the indoor navigation ontology. Furthermore, the indoor navigation ontology includes access points to the indoor space and junctions to enter corridors and enhance the network with the ability to include turns. This network is created using a semi-automatic approach and is the key to the visualization of transport and the movement.

By considering a graph based network representing transport ways or walking ways within a production line, the movement behaviour can be mapped on the network and visualized. Via a routing algorithm, for example Dijkstra, it is possible to create different paths. One path can represent the real path of the movement based on historically recorded data, by combining the visited equipment in a temporal order and tracked positions in between. Another path, for e.g. the same production asset, can represent the shortest path that combines the visited equipment of in a temporal order. Finally, two possible paths for each production asset can be compared with respect to length or areas traversed. This gives insight in the detailed movement behaviour and about deviations between the shortest or optimal path and the path used in reality. The calculation of real paths based on historical data and optimal paths can also be implemented in a data warehouse which is described section 4.1. Therefore, a spatial database management system, such as Postgres, has to be extended by a spatial cartridge, e.g. PostGIS, and a routing extension, e.g. pgRouting.

In order to monitor the transport behaviour based on extracted trajectories, it is also possible to sum up how often edges are traversed by a specific production asset. This highlights the edges mostly used and thus could be possible bottle necks or areas with special transport necessities.

Figure 6 highlights such a visualization using a graph based network. The graph based network is visualized using a green colour and connecting the equipment, facilities and specific nodes enabling the accessibility to the indoor space in red. A buffer is created around the network to represent the walking ways in a more appropriate way and also to compare the network more easily with real corridors in the production environment. To connect different production halls, virtual connections are established which are marked as blue buffers without a green network line. Based on this network, extracted tracks of production assets can be projected and compared. White spaces are used intentionally to hide detailed arrangements of equipment.

To sum up, the visualization of the transport or movement behaviour is based on a graph-based network which has to be implemented in a semi-automatic workflow. The network represents possible walking ways within the indoor production environment. Paths can be extracted from the historically recorded data and mapped onto the network to enable comparisons of paths or the visualization of bottle necks or critical areas showing potential to be improved.

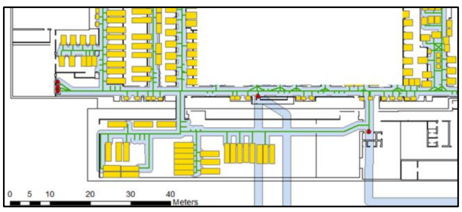

Figure 6: Example showing the graph-based network through the production line environment and possible walking ways as corridors.

4.3 Analysis of Transport Behaviour and Quality Measures

The analysis of spatial-temporal patterns of production assets is important, as especially for semiconductor production processes quality is a key to success. The ability to analyse the transport behaviour and quality implies a conceptualization of the movement and transport. Based on a conceptualization it is possible to use SOMs for an automatic data analysis (Kohonen, 2013). To model the movement of a production asset, it can be modelled as a sequence of equipment that shall be or has been visited by a production asset. These sequences of equipment can be used to compare similarities of different sequences and to analyse how different equipment are present in a sequence. A similar approach was implemented by Schabus et al. (2014) highlighting equipment which is used in similar groups of production assets. Figure 7 highlights a SOM showing the frequency of visited equipment. This analysis method enables the user to monitor if production assets have a different quality according to the likelihood of used equipment.

Figure 7 highlights one randomly selected component plane of a SOM showing the frequency of used equipment. By projecting production assets onto such a component plane, it can be seen if it is likely if a production asset will be processed by an equipment. The size of circles within the component plane represents the likelihood of occurrence, the bigger the more likely is the processing at this specific equipment.

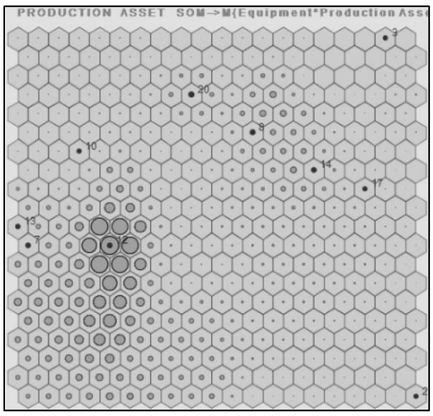

Figure 7: SOM showing a component plane of equipment highlighting the likelihood, if a production asset will be processed or not.

In addition to the likelihood of used equipment, another example uses SOMs to analyse quality measures of production assets based on an extracted sequence of equipment until a quality measure is triggered. This means, that each used equipment of a production asset is extracted until a quality measurement is triggered according to a certain pre-defined threshold. Conceptually, a triggering event separates the overall sequence of used equipment into sub-sequences, which will be used to compare the likelihood of an equipment resulting in a quality measure. Therefore, the SOM looks similar than in figure 7 with other component planes and quality measures are projected onto the SOM.

To compare the SOMs, they are integrated in an interactive website to explore a TRI-space approach based on spatial-temporal information of a production line environment. An example is created to compare SOMs with other spaces like time and location. The example implementation results in an interactive website showing two different types of SOMs, the location based on a map of the equipment and a time-slider to add the third component. The example shows that by changing the time on the time-slider, quality issues are projected onto the SOMs highlighting similarities with respect to the high dimensional attributive space and the triggering equipment is highlighted in the physical space.

Summing up, the analysis of the transport behaviour and quality measurements can be made possible by implementing a neural network algorithm such as SOM. Furthermore, the visualization itself bears high potential by comparing different possible tracks a production asset has taken or which way would be more optimal. Spatial-temporal data mining is implemented to analyse a high dimensional attributive space which is adjusted due to a conceptualization of relevant data. Thus, the exploration and combination is possible by considering a TRI-space based approach.

5 DISCUSSION AND CONCLUSION

This research paper elaborates on a GIS based approach to unveil the potential of smart manufacturing and Industry 4.0. The emerging interest in indoor geography, leads to an interdisciplinary approach coupling GISc, indoor geography, and smart production or industry 4.0.

To highlight how GIS can support smart manufacturing, the approach in this paper describes the integration of existing systems present at companies and how the combination of different data may help to gather new insights. A graph-based network is created that opens up the opportunity to map the movement of production assets by extracting the trajectories out of historical data. The visualization and analysis is done by comparing different paths such as an optimal path between used equipment or the tracked path of the production asset. Hence, the tracks can be mapped on the network. The spatial-temporal analysis part of the paper focuses on SOMs. SOMs have the capability of analysing a high-dimensional attributive space of big data leading to new knowledge when a visual exploration is done as follow-up process. This indicates, that it is possible to gain new knowledge out of existing data based on the utilization of GISc and existing data sources.

Future research directions include a variety of self-learning algorithms to gain new knowledge out of big data. Furthermore, the general application field of an indoor production environment bears huge potential concerning indoor navigation tasks. Furthermore, the real-time production relevant data of SCADA systems could be integrated in a Geographical Information System, which leads to new decision support possibilities (Back et al., 2014). Additionally, the paper contributes to indoor geography such as spatial-temporal analysis of movements, which helps to develop the simulation of movement behaviour further.

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Chapter 8

Spatially Linked Manufacturing Data to support Data Analysis

Manufacturers provide a variety of different heterogeneous data sources and systems. Therefore, a spatially Linked Manufacturing Data (LMD) approach is developed solving interoperability concerns of heterogeneous systems and data sources. This approach enhances manufacturing data with semantics and enables new analysis capabilities, such as a similarity analysis. Author activities and responsibilities are depicted in figure 8.1 (Schabus and Scholz, 2017b).

Title:	**Spatially-Linked Manufacturing Data to support Data Analysis**				
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Detailed Description of PhD (*Stefan Schabus*) **- Activities**					
▪ The candidate wrote main parts of the manuscript, supported with critical reviews and input of Johannes Scholz ▪ The structure of the journal was developed forehand by both authors. ▪ Development of the data structure and models ▪ Implementation of the Linked Manufacturing Data approach ▪ Management of internal release processes of the production company and external release processes of the publisher					

Figure 8.1: *Author Activity Description: Spatially Linked Manufacturing Data to support Data Analysis (Schabus and Scholz, 2017b).*

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Spatially-Linked Manufacturing Data to Support Data Analysis

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Abstract

The paper presents a Linked Data approach within a manufacturing organization to foster sharing, reusing, integrating and the collaborative analysis of datasets originating from different business units and heterogeneous data sources. The paper relies on a semiconductor company that serves as case study. The authors elaborate on manufacturing data and their representation in a spatially-enabled graph database, and as Linked Data based on an ontology describing the indoor space and production processes. A graph database enables data sharing as well as the semantic search and retrieval of data utilizing web-based services. The results present the analysis of historic, future and spatio-temporal data as well as the analysis of similarities of semantically-annotated linked manufacturing data.

Keywords:

linked manufacturing data, semantic annotations, smart manufacturing, graph databases

1 Introduction

In manufacturing industries, huge amounts of data with an inherent spatio-temporal dimension are generated during manufacturing processes. These manufacturing data satisfy the criteria for Big Data (De Mauro et al., 2016, p. 128): 'Big Data is the Information asset characterized by such a High Volume, Velocity and Variety to require specific Technology and Analytical Methods for its transformation into Value.' Manufacturing data comprise high volume and high velocity based on tracking of positions, processes and quality. The question of variety is tackled in this research, as the approach aims to solve semantic interoperability. Manufacturing data are necessary to support decision-making in near real-time. They are a result of measurement values provided by production equipment and sensors present in the production line. By monitoring the position of production assets using an indoor positioning system, spatial data are created. Combining them with manufacturing data, they become strongly intertwined with the spatio-temporal dimension (Davis et al., 2012; Zuehlke, 2010). Hence, it is important to generate knowledge from this data to support decision-making and learning from historical events. To do so, the data, which are created by different systems, need to be connected and integrated. This raises issues of semantic interoperability: there is a lack of explicit semantics, because there exist hardly any semantically-annotated base data from manufacturing equipment.

In order to overcome interoperability issues, the authors propose to semantically annotate the data, by making use of relevant ontologies in the field (Scholz & Schabus, 2014; Schabus & Scholz, 2015). This opens up possibilities for data- and knowledge-sharing with regard to existing spatio-temporal data (Klien, 2007), as has been shown for the case of Spatial Data Infrastructures (Lutz et al., 2009). The Linked Data paradigm is a recent shift in Geographic Information Science, offering a new way of structuring, publishing, discovering, accessing and integrating data (Kuhn et al., 2014). Linked Data are a collection of design principles and technologies around the Web of Data or Semantic Web. There, data are represented as triples (subject, predicate and object) in the Resource Description Framework (RDF) format. Data formatted in this way should conform to the Linked Data principles, which ensure that data are machine-readable, have a uniform resource identifier (URI) to denote things, and use the World Wide Web Consortium (W3C) standards, such as Web Ontology Language (OWL) or RDF. Data linking out to other data should use URIs to create an interconnected graph of knowledge. As RDF data are machine-readable, they seem well suited for information-sharing and for being shared between different applications.

The application context is a specific indoor space – a semiconductor manufacturing company. The indoor environment under review looks different from buildings for office or residential use, as no rooms are present and there are specific cleanroom restrictions. The production processes carried out in the production line have highly flexible characteristics, which means that the manufacturing line is not of 'conveyor belt' type with a fixed processing chain. This is due to the fact that several hundred production steps are necessary to create the finished product. Additionally, most production steps can be carried out on several pieces of equipment, which are often geographically dispersed over the production facility.

The research question of this paper can be summarized as: 'Does the translation of relational manufacturing data into semantically-annotated linked data contribute to new knowledge-generation based on data links and data analysis, i.e. the identification of similarities?' The authors focus on Linked Data in the context of manufacturing data as a new possibility to overcome the interoperability issues of heterogeneous data sources in manufacturing. Linked manufacturing data allow the sharing of semantically-annotated data across different business divisions of an organization. This increases the possibility of developing a decision support system for a manufacturer as well as leveraging analytical 'learning' from historical data.

The structure of the paper is as follows: section 2 covers relevant work; manufacturing data and their representation as Linked Manufacturing Data are the subject of section 3; section 4 presents the visualization of linked data and the analysis of similarities based on data semantics. Finally, we present a critical analysis of the results.

2 Relevant Work

This section covers related work that contributes to fields of scientific expertise covered in the paper. The authors emphasize indoor geography, modelling indoor space, and indoor navigation. In addition, the literature covers ontologies, semantics and linked data with respect to manufacturing data.

The average person spends 90% of their time inside buildings (Klepeis et al., 2001). Consequently, a number of research activities are currently being carried out to apply Geoinformation indoors. Early research elaborates on indoor modelling and pathfinding. In Raubal & Worboys (1999), for example, an airport serves as an example for agent-based indoor wayfinding. Several approaches to model indoor spaces exist, ranging from reducing the indoor space to a graph (e.g. Goetz & Zipf, 2011) to Building Information Models (e.g., Howell & Batcheler, 2005). Yang & Worboys (2015) as well as Scholz & Schabus (2014) employed ontologies to model indoor space. Scholz & Schabus (2014) used ontologies to model an indoor production environment with several requirements. Additionally, Schabus & Scholz (2015) proposed that space and time can help to improve decision processes in production environments.

Smart manufacturing is one of the main research fields to support decision-making in indoor production environm6ents, and to facilitate competitiveness (Davis et al., 2012). Most manufacturers collect data from processes, with explicit and implicit spatio-temporal reference. There is therefore a need to analyse and visualize such data. Data visualization in a spatio-temporal manner, using geovisual analytics, enables humans to identify patterns (Compieta et al., 2007; Andrienko et al., 2007; von Landesberger et al., 2016). Near real-time visualization could be of potential interest thanks to the emergence of wearable devices for employees and managers (Osswald et al., 2013). These devices allow a virtual view of performance and states of the manufacturing environment. Furthermore, spatio-temporal patterns can help to develop strategies and technologies to increase manufacturing efficiency – i.e. cost savings and increased performance (Nyström et al., 2006).

Semantics and ontologies are used in spatio-temporal modelling and have been discussed in scientific literature since the 1980s (Smith, 2001). Gruber (1993) defines an ontology as the formal specification of a shared conceptualization. A so-called domain ontology describes the specific domain in a general way, resulting in a formal description of the content and behaviour of a part of the physical world (Raubal & Worboys, 1999). Davis (1990) describes the elements of an ontology as entities, relations and applied rules. Grenon & Smith (2004) describe dynamic spatial ontologies that are capable of representing spatial relations. Types of ontologies are defined by Sowa (2014), who focuses on two in particular: a single large ontology or a collection of microworlds. These are described in greater detail by Yang & Worboys (2011). Sowa (2014) defines an upper-ontology as the most generic way to describe a concept at a basic level. The upper-ontology subsumes the domain ontology and the task ontology, which describe either the environment or the task – for example, navigation. The most specific ontology is the application ontology, combining the task and the domain in one single large ontology (Sowa, 2014).

3 Manufacturing Data and their Representation

To pave the way for the representation of manufacturing data as Linked Data (LD), there are a number of prerequisites that have to be fulfilled to transfer raw data into RDF. This section elaborates on a semantic description of manufacturing data, the indoor space and navigation actions, by utilizing ontologies. The authors use graph databases as physical storage for the generic ontology, as well as for the manufacturing data. To make manufacturing data ready for publishing as LD and using them thereafter, several issues need to be resolved. First, an appropriate semantic definition of the Universe of Discourse is necessary. The general concept of the Universe of Discourse is described by Boole (1854, p. 42):

'In every discourse, whether of the mind conversing with its own thoughts, or of the individual in his intercourse with others, there is an assumed or expressed limit within which the subjects of its operation are confined. […] Now, whatever may be the extent of the field within which all the objects of our discourse are found, that field may properly be termed the universe of discourse.'

In this paper, we restrict ourselves to a semiconductor manufacturing company, focusing on the manufacturing processes taking place in cleanroom facilities. In order to model the special indoor space, we utilize a navigation and indoor space ontology, describing the indoor space and the production processes at hand (Scholz & Schabus, 2014; Schabus & Scholz, 2015), referred to as IndoorOntology::Production in the remainder of this article.

For the IndoorOntology::Production, Scholz & Schabus (2014) developed a two-folded ontology in order to represent the indoor space and the manufacturing processes:

- Task ontology: indoor navigation ontology
- Domain ontology: production environment.

The main elements of the indoor space covered by the domain ontology are:

- ProductionUnit: describes the equipment pieces necessary for carrying out manufacturing processes; it is also used for facilities to store or deposit production assets;
- Corridor: denotes the spaces in a cleanroom that are walkable by humans and traversable by production assets;
- Barrier: limits the movement behaviour in the production line;
- Restriction: denotes specific restrictions that are due to cleanroom quality, contamination risks or maintenance, or to production data;
- Accessnode: links indoor and outdoor space (Schabus et al., 2015)
- NavigationAgent: the production asset.

The elements of the task ontology are navigation tasks and events (e.g. turn left or right), a graph-based structure with nodes and edges that enable routing in the indoor space. Additionally, the ontology includes the indoor space and affordances of production assets (i.e. the NavigationAgents). An example of such an affordance is that a staircase does not allow traversing a box of a specific product type, whereas an elevator does, which is due to the risk of damaging the production assets.

Linked Data concept for Manufacturing Data

In this section, we aim to show how heterogeneous manufacturing data, created by a number of heterogeneous systems and sensors, can be represented as LD. This section highlights the general concept and relations between IndoorOntology::Production, manufacturing and spatial data. In addition, the raw datasets are briefly described as a basis for understanding the LD concept.

In this study, the manufacturing data at hand describe the manufacturing process, the necessary equipment, the sequence of manufacturing processes and the production assets. Production assets are collected in boxes, and the production assets in the production 'line' may be at different levels of completion. In the production environment under review, a great number of different products are manufactured, and each product undergoes several hundred production steps (Osswald et al., 2013). The planned sequence of manufacturing operations for each product are subsumed in a so-called route. Each manufacturing operation can be carried out in several production units, which may be geographically dispersed over the cleanroom environment. The data of each executed manufacturing production process are stored in a relational database. The movement of each asset is tracked by an indoor positioning system based on ultrasound that logs its precise position throughout the entire production process (Dierkes & Fleisch, 2006). The indoor positioning system stores the data in a separate database/solution.

Spatial data for indoor manufacturing purposes are quite scarce; the spatial dimension has only recently become a focus for manufacturing industries. Hence, manufacturing equipment and sensors in the production line do not report the precise position. In order to overcome this lack of spatial data, we created a spatial dataset, representing the manufacturing environment under review, based on a dataset originating from a computer-aided design system. This spatial dataset (Scholz & Schabus, 2014; Schabus & Scholz, 2015) enables the possibility of linking non-spatial attributive data and the spatial dimension, which paves the way for spatial analysis capabilities. For indoor navigation purposes, we derived a network representation – i.e. a graph consisting of edges and nodes.

The general concept of the LD approach in this paper, which combines three datasets, is depicted in Figure 1. First, the IndoorOntology::Production (in blue) serves as a semantic reference for the LD. Second, the manufacturing data (in yellow) are compiled from different data sources. Spatial data (in green) are cross-sectional, and show defined links from the indoor ontology and the manufacturing data. These links ensure that each phenomenon described by LD can be referenced to the spatial dimension.

In detail, spatial data exist for:

- the indoor space, for routing purposes (nodes and edges)
- each production asset's trajectory (as points in a temporal sequence)
- each manufacturing device (and the connection to the indoor space – i.e. nodes)
- restrictions.

This approach facilitates an integrated spatio-temporal analysis of manufacturing data, as well as an exchange of data and information. Because attributive data are linked to the ontology, each individual dataset is amended with semantic information, which is necessary to link datasets from different systems (e.g. quality assurance vs. manufacturing system).

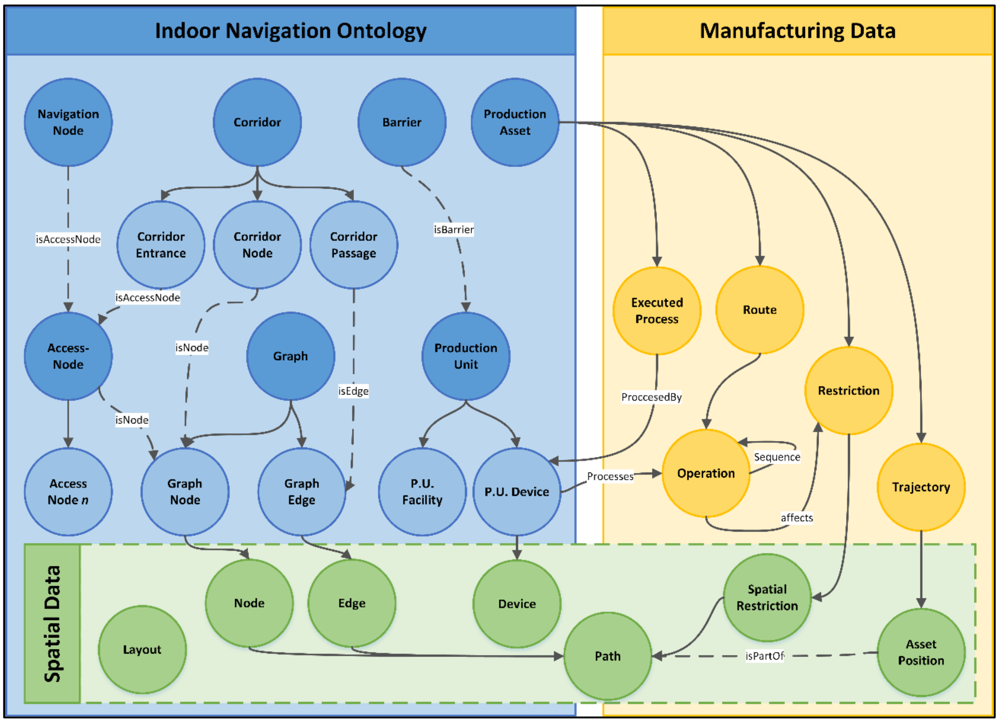

Figure 1*:* LD approach for manufacturing data. The indoor navigation ontology is marked in blue, the manufacturing data in yellow, and the spatial data in green. The arrows denote typed links between datasets and classes.

Linked Manufacturing Data – a Detailed View

This section highlights details of the data and the chosen LD approach, and shows the relations to the indoor ontology and the spatial data at hand. We restrict ourselves to significant examples that show the complexity present in this area of application.

Production assets are the main objects of interest in this manufacturing environment. In the case of this specific semiconductor manufacturing company, relevant datasets for production assets are mostly stored in various systems or in unconnected databases. Figure 2 depicts the LD approach for each production asset. Each asset is connected with typed links to a single route, which describes the sequence of manufacturing operations to be carried out. In addition, each manufacturing operation can be executed by one or more pieces of equipment (see also Figure 4). In the cleanroom, manufacturing devices are geographically dispersed over the production hall. Thus, the position of each device and the position of the production asset is of particular interest for finding the nearest machine for the next operation to be carried out. Therefore, the trajectory is linked to each production asset, including the spatio-temporal dimension. This guarantees a temporally ordered sequence of points with coordinates. The trajectory of an asset subsumes tracked asset positions, representing the movement of the asset through the production line. In addition, the manufacturing processes carried out and the corresponding equipment are linked to the production asset to offer the possibility of retrieving historic information for analysis.

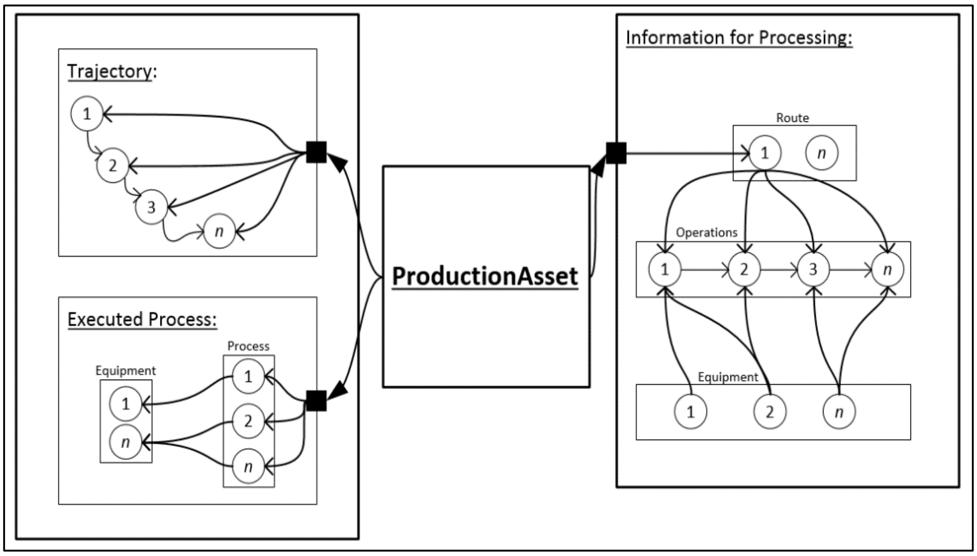

Figure 2: Datasets linked to each individual production asset.

Figure 3 gives a digital representation of a production asset, highlighting the linked information for each production asset. The figure is similar to Figure 2, but shows the typed linkages between the pieces of information, as well as the link to the abstract class 'ProductionAsset' (in blue) – which is a result of the IndoorOntology::Production. An individual production asset is equivalent to an individual in the ontology used. This is similar to an instance of an abstract class in software engineering. In addition, the structure of the attached trajectories is given, with points given in temporal order by the 'nextPosition' link. Executed processes (in red), are also stored in a temporal sequence, but here the system calculates the ordering by looking at the start and end times of each process.

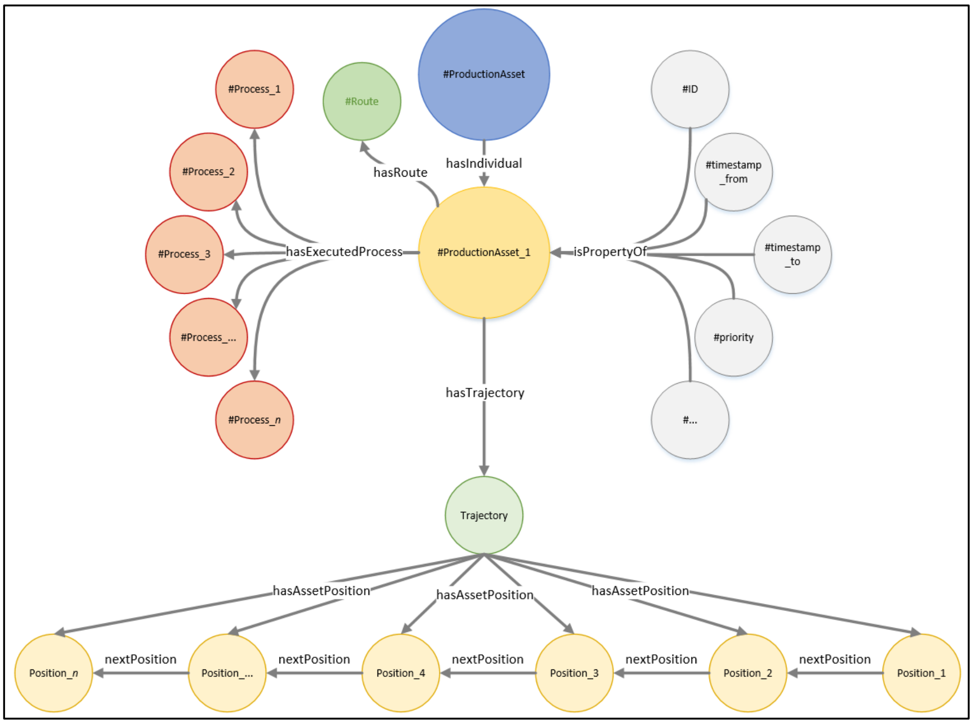

Figure 3: Digital representation of production assets and their linked datasets. Each individual production asset (in yellow) has a unique trajectory (in light green), where the points (in light yellow) are stored in a temporal sequence, denoted with the typed link 'nextPosition'. A unique Route is part of each production asset (in green). Each production asset has properties, which are marked in grey. Executed Processes are marked in light red.

Figure 4 shows a detailed view of the routes. Each production asset has a unique route, representing the manufacturing operations to be carried out. The example of a specific route, named 'Route_X', is linked to three operations/processes via the typed link 'hasOperation'. The temporal sequence of the operations is determined by the typed link 'nextOperation'. The execution of each operation is not restricted to one single manufacturing device, but can be done on several pieces of equipment, shown in yellow circles.

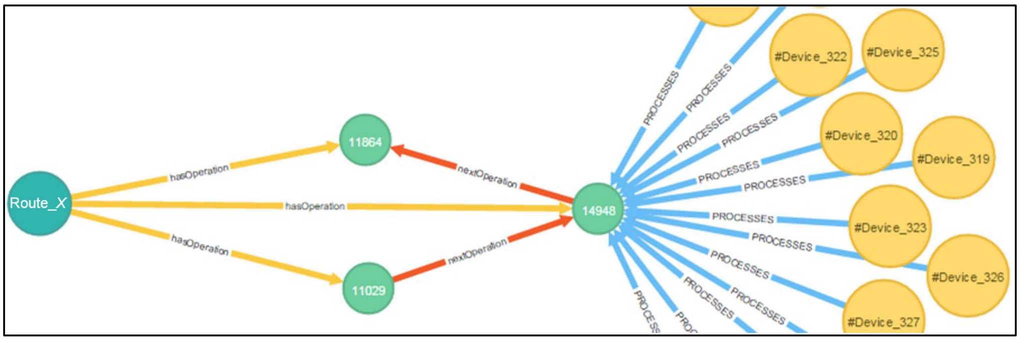

Figure 4: Detailed outline of a production asset and the associated Route. Here the specific Route, 'Route-X', has a number of attached operations, linked with 'hasOperation'. The operations are in sequence, shown by the typed links 'nextOperation'. Each operation is additionally linked to the devices that are capable of executing the specific task.

Implementation

In this section, we elaborate on the implementation of a spatial graph database, which is a digital representation of the Universe of Discourse as LD.

A general introduction to graph databases can be found in Robinson et al. (2015). Lampoltshammer and Wiegand (2015) show a successful combination of ontologies and graph databases in the context of GIScience. In this research, we use the graph database Neo4j to implement the LD approach described above. The spatial graph database we developed includes the semantic description of the manufacturing data, the indoor space and the navigation processes. It also incorporates space and time (Cattuto et al., 2013; Pluciennik & Pluciennik-Psota, 2014). The capability of Neo4j to store and query data with a spatio-temporal dimension leverages the potential for spatio-temporal analysis.

The Sesame framework (Broekstra et al., 2002) is suited for storing and querying RDF data residing in a graph database, in particular a Neo4j database. (This framework has recently been moved to the successor project, RDF4J (https://projects.eclipse.org/projects/technology.rdf4j).) The framework allows the querying of RDF data using SPARQL, or via RESTful services.

4 Data Analysis based on Linked Manufacturing Data

This section explores analysis examples of linked manufacturing data. The examples presented are based on the LD stored in the Neo4j spatial graph database. The data analysis focuses on the one hand on historic information, processing information and network routing capabilities, and on the other hand on the analysis of similarities based on data semantics and the spatial graph database developed during research.

Analysis of Linked Manufacturing Data

In order to show the linkage of a route, the associated operations and the possible processing equipment are illustrated in Figure 5. On the left-hand side, the displayed route, "Route_Y", is linked to three operations via the relationship 'hasOperation'. The sequence of operations is shown via the relationship 'nextOperation'. The relationship 'PROCESSES' links operations to possible processing equipment. The right-hand side of the figure illustrates how devices can carry out either a single operation or a variety of operations, and, vice versa, how an operation can be executed by a variety of devices.

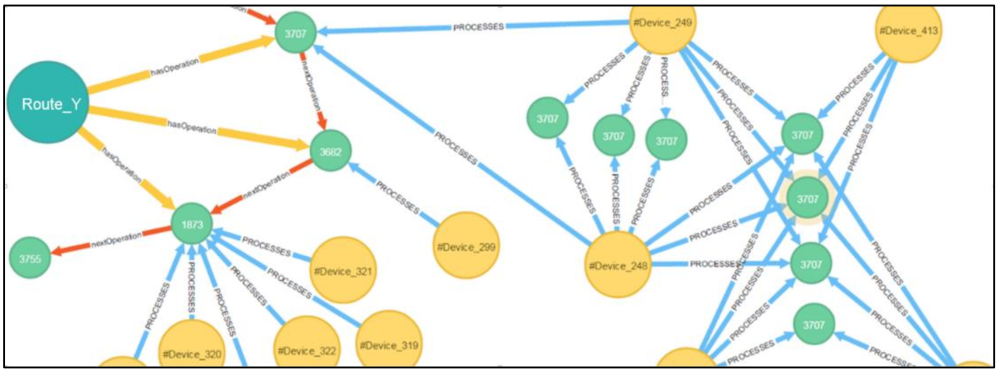

Figure 5: Manufacturing data showing the linkage from a production asset's route, the corresponding sequence of equipment, and possible processing equipment.

Historic information is necessary for quality assurance, monitoring and reporting. Therefore, Figure 6 shows the production asset as the focal point of the visualization. A production asset has several executed processes, and each executed process is linked via the relationship 'hasExecutedProcess'. The stored executed processes include the temporal order, given via timestamps for the processing tasks carried out, to enable successful monitoring. Via the relationship 'ProcessedBy', the spatial graph database stores the link to the device which processed the asset. Figure 6 illustrates how one device was used in several manufacturing steps.

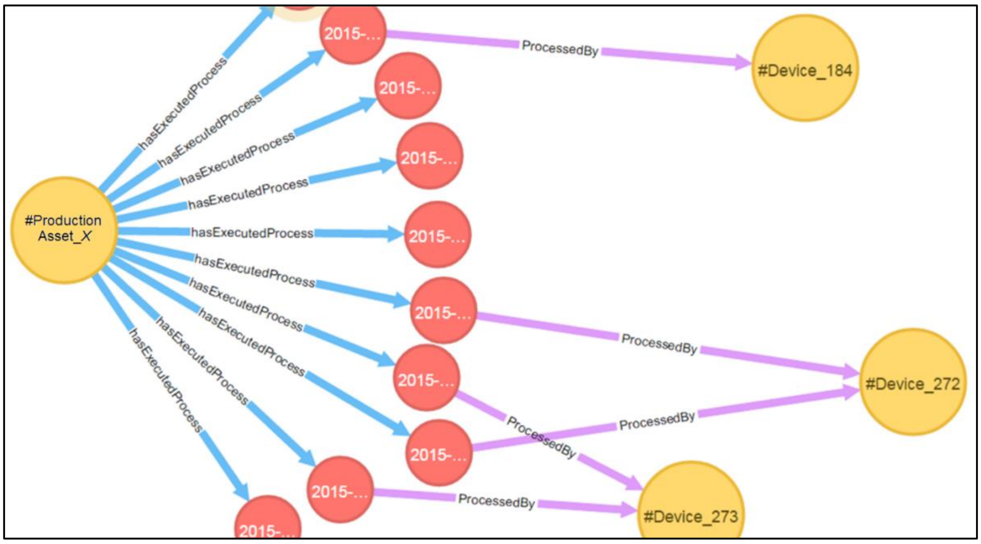

Figure 6: A single production asset 'ProductionAsset_X' and its executed processes, showing that some processes are executed by the same production device.

Network information is important for smart manufacturing purposes and thus especially for the autonomous transportation of production assets within a production line. Figure 7 illustrates the modelling of a routable graph-based network. This network which consists mainly of non-spatial nodes and relationships in the graph database that enable monitoring. For routing purposes, the network is established via the red edges, visualized in Figure 7, and grey nodes (corridor nodes, device nodes) that are semantically annotated. Each of these nodes is linked via the relationship 'hasSpatialNode' to a spatial object in order to enable visualization and analysis. Similarly, the relationship 'linkedTo' binds the incoming/outgoing edges to each node for the spatial view, which is then added via the relationship 'hasSpatialEdge'.

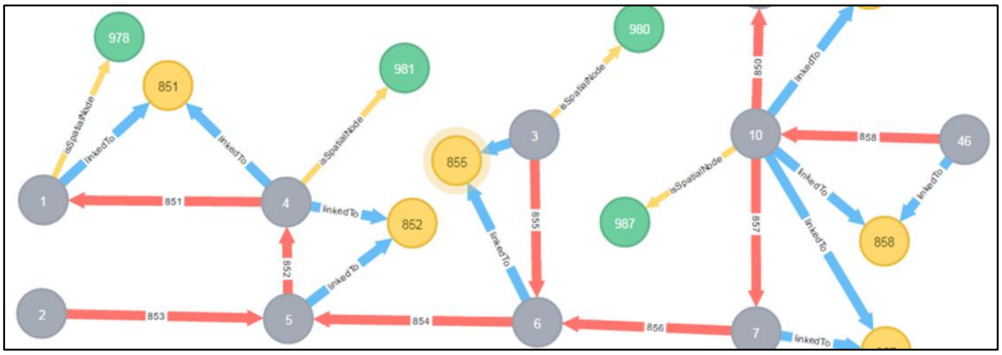

Figure 7: Routable Network in the spatial graph database and a link to spatial information, including the capability to link spatial suitability to and corresponding affordances to a potential route optimization.

Similarity Analysis of Linked Manufacturing Data

Figure 8 shows an example of a similarity analysis based on semantically annotated linked manufacturing data. This figure focuses on the similarity of the types of production assets. Therefore, the spatial graph database is queried to identify paths between assets based on typed links such as 'fromType' and 'hasSubType'. By assuming that the length of the path or the edge count between assets is affecting the similarity of assets, Asset_1 and Asset_2 (3-Edges) are more similar than Asset_1 and Asset_3 (4-Edges). In addition, Asset_1 and Asset_5 are completely different, as there is no possible connection via the defined relationships. This type of similarity analysis can be useful for monitoring quality issues and identifying assets affected after a possible incident.

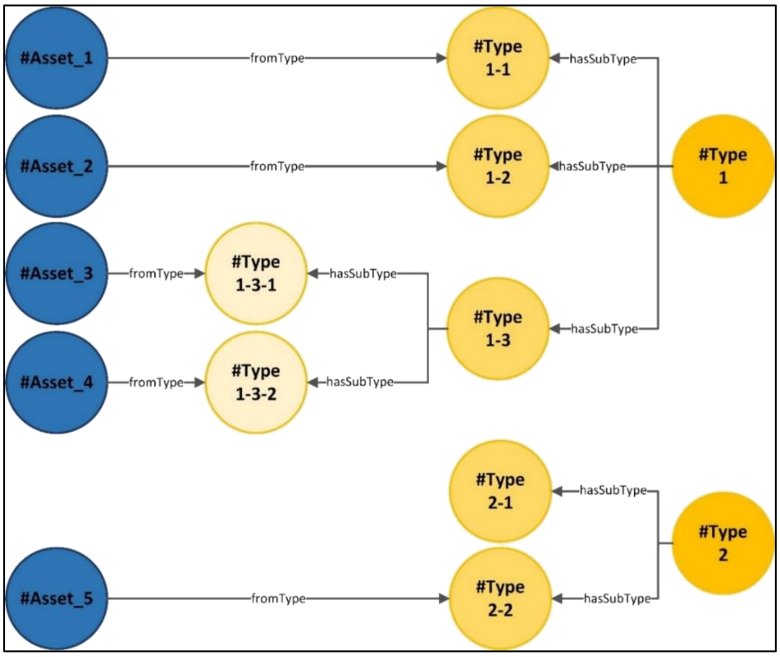

Figure 8: Similarity Example based on the Semantic Annotation of Asset (Sub)-Types.

5 Conclusion and Discussion

This paper elaborates on an approach to migrate manufacturing data into a LD approach. This utilizes the expressive power of semantics to annotate manufacturing data. The approach makes use of an ontology that describes the indoor space and the manufacturing process, including real-world objects and processes such as transport, navigation, production assets and devices. The research includes the representation of manufacturing data in a spatial graph database and publishes them to support RESTful services: as 'raw' data in the spatial graph database (queryable via Cypher). Because the data in the graph database are accessible via web-based services (i.e. RESTful services), the data can be reused within an organization. Currently, data discovery and/or data sharing present shortcomings in manufacturing organizations. These issues could be resolved to some degree with the help of semantic interoperability. The analysis capabilities support the evaluation of historical data as well as the autonomous transport of production assets in a smart manufacturing environment.

In answer to the research question 'Does the translation of relational manufacturing data into semantically annotated linked data contribute to new knowledge generation based on data links and data analysis, i.e. identification of similarities?', the authors conclude that a LD approach can contribute to an increase of the spatio-temporal analysis capabilities. The conclusion is justified by the possibility of the LD approach to share data, using a standardized interface via web-based services. The LD approach may be beneficial for large manufacturers with vast amounts of data who could utilize semantically tagged data. This enables any user to gain new insights and extract similarities for a given question, based on the explicit semantics of the data. The LD approach can be used to query – and combine – datasets from servers which are geographically dispersed. Machines are able to collect data automatically, and perform reasoning tasks with the help of the semantics. In combination with web-based services, this enables seamless data-sharing, overcoming organizational borders in both the syntactic and the semantic dimensions.

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Chapter 9

Semantically Annotated Manufacturing Data to support Decision making in Industry 4.0: A Use Case Driven Approach

To show the result of the new structured manufacturing data as LMD, the included publication refers to application of carried out use-cases. Therefore, the presented publication covers the use-cases incident analyis and a potential bottle neck analysis, which incorporates spatial-temporal data and semantics. Figure 9.1 states the author activities and responsibilities (Schabus and Scholz, 2017a).

<table>
<tr><td>Title:</td><td colspan="5">Semantically Annotated Manufacturing Data to support Decision Making in Industry 4.0: A Use-Case Driven Approach
Bringing new Structure into existing Data to support Smart Manufacturing</td></tr>
<tr><td>Authors:</td><td colspan="5">Stefan Schabus – Infineon Technologies Austria AG, Villach Austria
Johannes Scholz – Graz University of Technology, Institute of Geodesy, Research Group Geoinformation, Graz, Austria</td></tr>
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<tr><td colspan="6">Short Description of Authors Activities</td></tr>
<tr><td>Stefan Schabus:
(Candidate)</td><td>▪ Wrote mainly the manuscript together with Johannes Scholz
▪ Modelling of the connectivity between spaces
▪ Responsible for Revision</td><td>Johannes Scholz:</td><td colspan="3">▪ Supported the candidate writing the manuscript
▪ Critical Review and Feedback about content
▪ Responsible for Author Correspondence and Presentation</td></tr>
<tr><td colspan="6">Detailed Description of PhD (Stefan Schabus) - Activities</td></tr>
<tr><td colspan="6">▪ The candidate wrote main parts of the manuscript,
    ▪ Johannes Scholz supported the writing of the manuscript, especially focusing on section 2
    ▪ Forehand, the structure was developed by both authors
▪ Implementation and of the Linked Data Concept enhancing Data with semantic annotations
▪ Modelling and Analysis of Manufacturing Data
▪ Management of internal release processes of the production company</td></tr>
</table>

Figure 9.1: *Author Activity Description: Semantically Annotated Manufacturing Data to support Decision making in Industry 4.0.*

Semantically Annotated Manufacturing Data to support Decision Making in Industry 4.0: A Use-Case Driven Approach

Bringing new Structure into existing Data to support Smart Manufacturing

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***Abstract*—Smart Manufacturing or Industry 4.0 is a key approach to increase productivity and quality in industrial manufacturing companies by automation and data driven methods. Smart manufacturing utilizes theories from cyber-physical systems, Internet of Things as well as cloud computing. In this paper, the authors focus on ontology and (spatial) semantics that serve as technology to ensure semantic interoperability of manufacturing data. Additionally, the paper proposes to structure production relevant data by the introduction of geography and semantics as ordering dimensions. The approach followed in this paper stores manufacturing data from different IT-systems in a graph database. During the data integration process, the system semantically annotates the data – based on an ontology, developed for that purpose - and attaches spatial information. The approach presented in this paper facilitates an analysis of manufacturing data in terms of semantics and the spatial dimension. The methodology is applied to two use-cases of a semiconductor manufacturing company. The first use-case deals with the data analysis for incident analysis utilizing semantic similarities. The second use-case supports decision making in the manufacturing environment, by the identification of potential bottlenecks in the semiconductor production line.**

Keywords—Semantic Data; Smart Manufacturing; Industry 4.0; Spatial Data; Geography

I. Introduction

Manufacturing industry needs to focus on the competitiveness of manufacturing processes, as global markets tend to be increasingly competitive. Therefore, any manufacturing company works on strategies to increase productivity, efficiency, performance and to realize cost-savings [1; 2]. To achieve these long-term goals, IT-technology has been identified as promising “tool”. Utilizing digital technology in the manufacturing sector leads to Industry 4.0 or smart manufacturing activities. Digitalization of manufacturing processes makes use of cyber-physical systems, Internet of Things and cloud computing [3; 4; 5].

Currently, huge amounts of data are generated, e.g. by sensors and manufacturing devices, that are intended to keep track of processes, quality issues and also transportation processes of production assets. Due to the fact, that a great variety of proprietary IT-systems are present in manufacturing enterprises, the collected datasets can hardly be combined in an interactive manner. The variety of IT-systems is currently justified, because each system serves a certain purpose – and is often required by a single department. In recent times, the necessity to make an integrated analyses of collected datasets is growing, partly based on Industry 4.0 initiatives. Hence, the lack of existing interoperability to share and integrate datasets within manufacturing companies becomes evident. Interoperability in this context is regarded as semantic interoperability. While syntactic interoperability can be easily achieved with (spatial) ETL tools, semantic interoperability enables an ad-hoc sharing and analysis of different datasets.

To utilize the potential of the collected manufacturing data, this paper proposes to add semantic annotations and geographical information, and use these added information layers for analysis and decision making purposes. Therefore, the indoor manufacturing space and the manufacturing processes need to be semantically described. Ontologies are an appropriate way to formally describe a universe of discourse [6; 7; 8]. Ontologies consist of entities, relations connecting the entities and rules [9]. Recently, the modeling of cyber-physical systems proved successful [12]. Papers [10; 11] elaborate on the spatial dimension of ontologies. In the context of geography and indoor space, ontologies are used to model indoor space [13; 14; 15]. To utilize ontologies in an IT architecture, the concept of Semantic Web offers the possibility to share data and their meaning – i.e. their semantics [16]. Semantic methodologies have been recently applied in smart manufacturing environments [4; 17; 18]. These approaches mostly utilize semantic web services to share semantics and/or semantic annotations of manufacturing data.

The research question of this paper focuses on the integration of heterogeneous manufacturing datasets with the help of ontologies and the geographical dimension. Additionally, the paper elaborates on the question if semantics and geography can help to analyze manufacturing datasets and in turn support decision-making.

The methodology in this paper is as follows. First, we develop an ontology for manufacturing purposes that is based on an indoor navigation ontology [13]. This ontology describes manufacturing processes, production assets, manufacturing devices, as well as indoor manufacturing environments (i.e. cleanroom). In addition, the ontology includes geographical phenomena of the entities, such as positions of production assets over time, as well as a topological model of the indoor space – for routing and navigation purposes. Based on the developed ontology, heterogeneous datasets are integrated in a Graph database. The integration process includes a semantic annotation of the datasets and the establishment of typed links between abstract classes and entities, as well as between entities. To justify the approach, we evaluate the potential of semantically annotated and geographically amended data in two use-cases. The use-cases are located in a semiconductor manufacturing company, a highly flexible and complex manufacturing environment. Use-case #1 deals with incident analysis in the manufacturing line and the search for similar products that are potentially damaged. Use-case #2 deals with identifying bottlenecks – in terms of manufacturing capacity – in the semiconductor manufacturing line under review.

As stated before, both use-cases are located in a semiconductor manufacturing facility with cleanroom restrictions. The following paragraph is intended to give a brief overview of the semiconductor manufacturing facility. Each production asset requires several hundred manufacturing steps from raw silicon wafer to the final microchip. Each step can be processed by several devices, which may be geographically dispersed over the production facility. In the facility, assets with different degrees of completion are present at the same time. In addition, several hundred different products or product types are manufactured simultaneously in the same facility. Each single production asset may have varying manufacturing time – lasting from several days up to a couple of weeks. Furthermore, the proportion of products and the overall manufacturing quantity is changing on a weekly basis, depending on the customer needs. This flexible production is the reason for the absence of a conveyor belt. Thus, production assets are mainly transported on trolleys from one production step to the next one. Further details of the universe of discourse are to be found in literature [13; 19; 20].

The reminder of the paper is organized as follows: Section 2 elaborates on semantic annotated manufacturing data and the modeling aspects thereof. In addition, the storage in a graph database is described. Section 3 focuses on the analysis of manufacturing data and the data's semantics based on two selected use-cases: #1) incident analysis in the manufacturing line and #2) potential bottleneck identification. Section 4 is a conclusion and discusses potential future research directions of smart manufacturing based on semantically annotated manufacturing data.

II. Modelling, Storing and Publishing Semantically Annotated Manufacturing Data

The following section elaborates on the modelling aspects of the universe of discourse. Furthermore, we focus on the data storage in a spatial graph database with additional semantics. Finally, the visualization of semantic annotated data in the spatial graph database and the querying thereof are highlighted. The data model in a graph database follows a graph-oriented structure. Due the fact that the data are machine readable – and may be shared as Resource Description Framework (RDF) [21] – the approach ensures semantic and syntactic interoperability.

A. Spatial-temporal Ontology to model Manufacturing Environment

An ontology in the context of knowledge sharing "is a specification of a conceptualization" [8]. Thus, an ontology is a description of the concepts and relationships that can exist in a universe of discourse [6]. [10] and [22] describe the modeling of the spatial domain with the help of ontologies. As ontologies describe the universe of discourse in a formal way, they can help to foster semantic interoperability [23; 24].

The ontology developed in this context is based on an Indoor Navigation Ontology in a production environment [13]. After a review of the existing Navigation Ontology, some additional entities and relationships are added - for the purpose of modeling manufacturing processes accurately. Figure 1 shows the ontology published by [13] with the most important amendments made. Oval shapes represent classes, and relationships are illustrated with solid arrows. The root element – thing – has several top-level entities like Navigation Agents (i.e. production assets), Corridors, Graph, Production Unit.

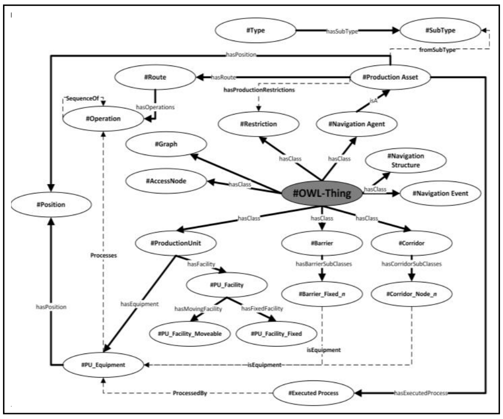


Fig. 1. Snapshot of the adapted ontology by [8] showing class hierarchies as solid arches and added semantics as dashed arches.

The class corridors represents the corridors in the production hall, which have several corridor nodes – each one having a geographical position. Each corridor node is connected with a piece of manufacturing equipment. The class graph denotes the underlying geographical structure necessary for routing and navigation purposes. The production assets are categorized in types and sub-types, besides a geographical position. The class route – connected with the production asset – holds information on the sequence of manufacturing operations (planned and historic operations). In addition, each manufacturing equipment is able to process 1-n operations. A production unit is either a facility – like a table or shelf – or a manufacturing equipment. Facilities are moveable or fixed. In addition, figure 1 shows that movement barriers exist in the manufacturing environment having several sub-classes, such as fixed barriers. The dashed arrows represent added relationships, like that the class "Barrier_fixed_*n*" may be an equipment.

The geographical information, present in the model at hand, is stored in the classes position and graph. The class position contains points with an ordered pair of x/y coordinates amended with the floor information. Each piece of equipment, production facility and each production asset have a geographical position. In addition, the model offers the possibility to store historical positions of each entity – resulting in a trajectory for each aforementioned entity. The entity graph represents a routable network consisting of vertices and edges, connecting entities in the indoor space (i.e. manufacturing devices, shelves, access nodes, etc.). Each vertex of the network has a specific position, which makes use of the position entity – i.e. having an x/y coordinate.

The data model contains a temporal component as well. Each production asset has an associated planned manufacturing route – in this context a sequence of manufacturing operations. In addition, the ontology allows the storage of the historic manufacturing operations in a temporal order, with the help of a temporal ordering.

B. Storage and Analysis in a Graph Database

A graph database is a database management system that is capable of creating, reading, updating, and deleting data in form of graphs in a database. A general introduction of graph database and their fundamental concepts are presented in [25]. The combination of ontologies and graph databases in the field of Geographic Information Science are published in [26]. Graphs are a collection of ordered pairs of vertices and edges. In this context, vertices correspond with entities and relationships connect entities – thus corresponding with edges. This allows the modelling of real world in terms of graphs, e.g. supply-chains, road network, or medical history for populations (see e.g. [27]). They became very popular due to their suitability for social networking, and are used in systems like Facebook Open Graph, Google Knowledge Graph, or Twitter FlockDB [27].

To make use of the developed ontology for data analysis purposes, the authors migrate the ontology – stored as Ontology Web Language (OWL) - into the graph database. Hence, the abstract entity classes and their relationships are part of the graph database. Subsequently, relevant manufacturing data are migrated into the graph database and semantically annotated – to open up the possibility for semantic data analysis. The following datasets are migrated into the graph database (see Figure 2):

- Manufacturing data
    - Historic manufacturing data of production assets including quality related data
    - Planned manufacturing operations for each production asset
- Spatial data: i.e. routable graph structure, manufacturing equipment positions, trajectories of production assets.
- Attributive information: e.g. attributes of production assets, equipment, spatial/temporal movement restrictions;

The migration of the data sets into the graph database is a process that uses spatial and non-spatial data from object-relational database management systems (DBMS) and other proprietary IT-systems (e.g. Computer Aided Design Systems). The process analyzes the data with respect to the developed ontology. Thus, we identify individuals of abstract entities, create the relationships as typed (annotated) edges based on the ontology, and assign the properties of each individual. An example is the analysis of historical manufacturing data. Each individual production asset and its trajectory is queried in the corresponding object relational DBMSs. For each production asset, the process creates a new vertex in the graph database, with a typed (semantically annotated) relationship to the abstract entity 'Production Asset'. Future processing information is added via linked operations, which are executable at a certain equipment. Historic manufacturing data, describing the asset history, like executed processes, processing equipment and the asset's trajectory are stored as well. The trajectory is a sequence of asset positions – where the positions are ordered by time.

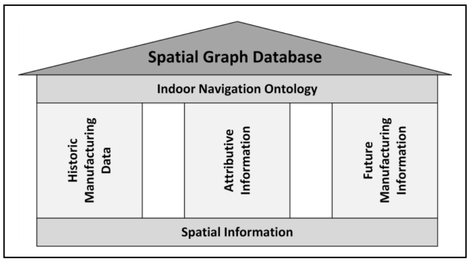


Fig. 2. Pillars of the spatial graph database that serves as data pool for semantically annotated historic, attributive, future and spatial data.

Figure 3 shows an example visualization of the spatial graph database, which is implemented utilizing the graph database 'Neo4j'. The visualization capabilities of Neo4j allow the displaying of graph elements. A single piece of equipment – i.e. an individual – can be visualized including the relationships. In Figure 3 an equipment is depicted that is linked to attributes such as name, location, or possible processes. In addition, this specific equipment is a barrier for the transportation of production assets.

Figures 4 illustrates two production assets and their relationships in the graph database. In this example, it is clearly visible that each asset is processed at specific pieces of equipment. In order to analyze this fact with the help of algorithms, any graph database supports the application of algorithms originating from graph theory.

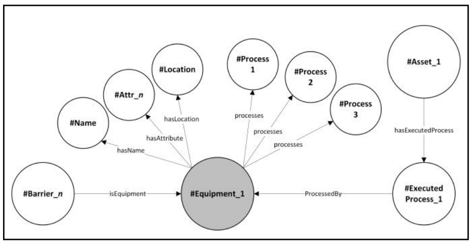


Fig. 3. Visualization of the spatial graph database with the equipment as a center point. It includes historic information via the executed process, attributive information via hasName or hasAttribute and future information via possible executable processes at the equipment.

A detailed analysis of the data present in the graph database is based on graph theoretical algorithms, such as breadth-first search and shortest-path algorithms, in conjunction with the inherent semantics and geographical information. Due to the fact, that the edges are semantically annotated, any graph analysis algorithm can make use of that information. An example is the dynamic identification of existing paths between entities (i.e. vertices) that supports the analysis of similarities of entities. Such similarities may be: similar location, similar processing equipment, or similar trajectories. In figure 4, an example for the similarity evaluation of two production assets is given. Asset 1 and 2 have a variety of attributes, and a number of processing equipment but only one path from asset 1 to 2 exists via equipment 3 – exploiting the "*processedby*" relationship. Hence, equipment 3 processed both assets. By adding the temporal dimension, incident analysis becomes possible. Incident analysis tries to identify potentially affected production assets of an incident – like an equipment failure, contamination issue or cleanroom problem. Therefore, the analysis of an assets' position at each time instant is inevitable, to identify which assets have been present in the affected area at a specific time (interval).

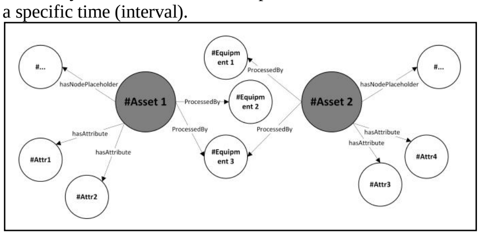


Fig. 4. Example showing the data present in the graph database. If a path along the 'ProcessedBy'-edges from asset 1 to asset 2 via equipment 3 is possible, we can conclude that both were processed by equipment 3

III. Analysis of Manufacturing Data based on Semantically annotated Data: Use-Cases

The analysis of semantically annotated manufacturing data is shown based on two use-cases. Both are based on the developed ontology and manufacturing data present in the graph database. The first use-case deals with incident analysis, whereas the second use-case elaborates on the identification of possible manufacturing bottlenecks. Both use-cases rely on historic manufacturing data, which are structured and analyzed to identify similar movement patterns and similarities regarding the utilized equipment.

A. Incident analysis – Identification of similarities with respect to Space and Time

An incident is an "an unplanned, undesired event that hinders completion of a task and may cause injury or other damage" [28]. Incidents may include minor human operator injury, minor damage to smaller system parts, or failure of a component – but do not disrupt the system as a whole [29]. In the context of this paper, incident analysis is regarded as the process of finding production assets that are similar to assets having quality issues. An incident in this respect can be an equipment failure, contamination or cleanroom problem. In general, only a sample of the production assets have to undergo a full quality check at the end of the production line. Hence, if quality anomalies exist, similar production assets need to be identified and quality checked in order to minimize the possibility of delivering defective products.

The incident analysis highlighted in this use-case, elaborates on an analysis with the help of spatial queries and the determination of similarities on the level of production assets. Based on a defective production asset, an incident – here a malfunctioning air cleaning system over a certain time span – is identified as root cause. This incident might lead to contamination issues on production assets. Figure 5 depicts the occurred incident in the manufacturing environment with a red circle. The affected area is visualized as a circular red circular object in Figure 5. In order to limit the complexity of the semantic query, the production assets traversing the incident area are selected. Therefore, the trajectories of the assets are analyzed, which is depicted in Figure 5.

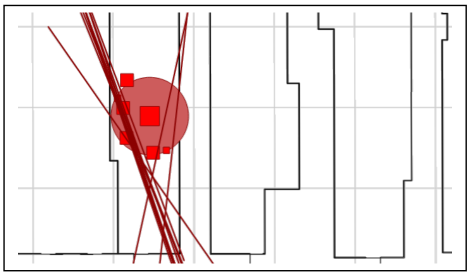
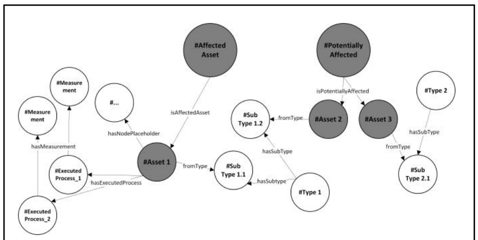


Fig. 5. Trajectories of production assets crossing an incident area. The area is limited by space and time. The intersecting lines indicate assets that have been potentially affected by the incident, which is marked with a big red circle.

The spatial query in the graph database is as follows: '*spatial.intersects('layer_tracked_positions_', Incident_Area) YIELD node_asset RETURN node_asset, node_geometry'* and returns the asset identifier and asset geometry to be mapped. In addition, this result set is further reduced by duration of the incident. The resulting set is the starting point for the semantic analysis. The spatial-temporal selection reduces the number of potentially affected assets from of a few thousand to a few hundred.

In this use-case, the defective asset serves as reference asset for identifying similar possibly affected assets. Thus, Figure 6 shows the methodology of identifying assets using the spatial graph database and semantics. We have the possibility to identify similarities between the faulty asset and potentially affected assets, by analyzing the graph. In Figure 6, the possible paths from the affected asset 1 to potentially affected assets 2 and 3 are visualized. The analysis makes use of the graph structure, and calculates the path length between the assets strictly allowing edges annotated as "*fromType*" and "*hasSubType*". Hence, asset 1 and 2 are similar because the shortest path between them comprises four edges – both have a same product type. Asset 3 has a different product type and subtype resulting lower similarity – so there is no connectivity between asset 1 and 3. In Figure 6 the pseudocode of the analysis in the graph database is depicted.




```
Pseudocode:
----------------------------------------
MATCH   (PotentialAffectedAsset)-[:HAS_MEASUREMENT_VALUE]->(MEASUEREMENTS)
WHERE   EXISTS ((PotentialAffectedAsset)-[*]-(AffectedAsset))   AND
        MEASUREMENT.TIME AFTER (TIME_FROM_INCIDENT)             AND
        MEASUREMENT.VALUE IN RANGE (
                MATCH (AffectedAsset [:hasQualityIssue]->(RiskThreshold)
                RETURN RiskThreshold.RangeValue)
RETURN  PotentialAffectedAsset.id, MEASUREMENT.value AS ThresholdValue
```

Fig. 6. Identification of similarites between an identified affected asset and potentially affected assets using the graph database and semantics. A connecting path between asset 1 and 2 is possible due to similar product types. The pseudo code shows an evaluation of existing measurement values of the potentially affected asset.

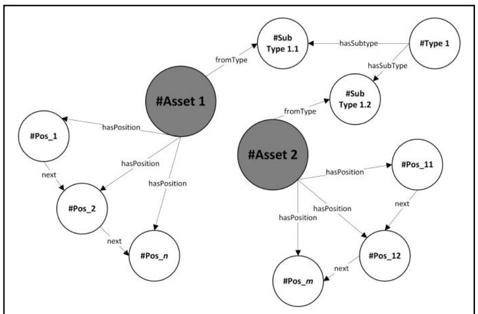
B. Identification of Potential Bottlenecks based on Historic Data

The identification of potential bottlenecks is a crucial task for the manufacturing line management, as bottlenecks may negatively influence the efficiency of the production line. In this paper, we identify bottlenecks based on the geographical information associated with the production assets. We analyze the trajectories of production assets and potential bottlenecks.

Bottlenecks in a production line are present if the capacity of manufacturing equipment for a specific task is lower than the inflow of assets to be processed. Thus, assets need to be stored in shelves, and have to "wait" until they can be processed. The trajectories of assets are an indicator for detecting bottlenecks. An evaluation of the movement of assets – i.e. distance from one position to the next position – gives an indication on the potential bottlenecks present in a manufacturing line. If an asset does not move over a certain period of time it regarded as being waiting.

To determine assets with a "high" waiting time, we use the following methodology. The waiting time of an asset is regarded as timespan between being placed in a shelf, and the start of the next manufacturing operation. First, we calculate an average waiting time and standard deviation over the last month for each asset type, per operation and equipment. This number serves as indication for the "normal" waiting time in the factory. Thus, we calculate the recent waiting time for each asset type, per operation and equipment. This is done using a moving average waiting time calculation, with a two-hour window. Assets having a higher waiting time than the 2-sigma range of the normal waiting time are classified as "delayed". By exploiting the geographical information of each asset, it is possible to identify clusters of delayed production assets – i.e bottlenecks – for different asset types, operations, or pieces of equipment. In addition, an analysis of historical bottlenecks may reveal spatial-temporal patterns of a "congested" production line that could be of interest for factory managers.

Figure 7 shows the pseudo code for the proposed analysis. The code identifies all waiting times for similar assets by selecting one asset of interest and identifying therefore all similar assets. The result can be visualized as a heatmap depicting bottlenecks in the indoor manufacturing environment.




```
Pseudocode:
----------------------------------------
MATCH   (Asset)
WHERE   EXISTS (Asset)-[*]-(Asset)  AND
        DISTANCE(Point(X), POINT(Y)) LESS THAN 10 Meter AND
        (
            MATCH (Position)
            WITH MEAN(Position.Timestamp >= Current_TIMESTAMP - 1Month) AS WaitingTime_LongTerm
            WITH MEAN(Position.Timestamp >= Current_TIMESTAMP - 2Hours) AS WaitingTime_Current
            WHERE WaitingTime_Current >=  2*Sdtdev(WaitingTime_LongTerm)
            RETURN Position
        )
RETURN  Asset.Position AS PotentialBottleneckArea
```

Fig. 7. Identification of bottlenecks of production assets based on the waiting time.

IV. Conclusion and Discussion

To conclude, the paper elaborates on the creation and analysis of semantically annotated manufacturing data. Based on two use-cases we show that semantics and geographical information can contribute to improving decision making in manufacturing environments. Both use-cases rely on data analysis of semantically annotated (spatial) data in a graph database. Semantic annotations in the graph database are a result of an ontology, describing the indoor semiconductor-manufacturing environment.

The data analysis in both use-cases reveals the potential of a combined geographical and semantical data analysis. In addition, the integration of various data sources in a graph database and their semantic annotation serve as basis for the use-cases discussed in the paper. This underpins the argument to strengthen semantic interoperability – also in manufacturing companies. Hence, intelligent data sharing and publishing strategies like Linked Data [16] could be an appropriate strategy for manufacturing companies. A Linked Data approach within a factory could open up the possibility to semantically query available datasets using SPARQL. Additionally, the geographical domain could be considered by using the query language GeoSPARQL [30].

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Chapter 10

Mapping Parallels between Outdoor Urban Environments and Indoor Manufacturing Environments

A transportation task is analysed based on parallels between outdoor urban and indoor manufacturing environments. The analysis focuses on a task-decomposition and solving of tasks based on affordances. Based on such a task-decomposition, a task can be solved either indoor or outdoor. The author activities of the publication are presented in figure 10.1 (Schabus et al., 2017).

Title:	**Mapping Parallels between Outdoor Urban Environments and Indoor Manufacturing Environments**				
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Short Description of Authors Activities					
Stefan Schabus: (*Candidate*)	▪ Wrote mainly the manuscript together with Johannes Scholz ▪ Internal Release Process	**Johannes Scholz:**	▪ Wrote the manuscript together with Stefan Schabus ▪ Author correspondence and submission	**Thomas J. Lampolts-hammer:**	▪ Literature Input ▪ Critical reviewed the written manuscript ▪ Language Review
Detailed Description of PhD (*Stefan Schabus*) - **Activities**					

▪ The candidate wrote main parts of the manuscript
  ▪ Introduction & Relevant Work
  ▪ Johannes Scholz supported the candidate with main input for problem solving characteristics and relevant work
  ▪ Analysis of a transportation task in an urban environment, manufacturing environment and a general task
▪ The structure of the journal was developed forehand by the authors
▪ Management of internal release processes of the production company					

Figure 10.1: *Author Activity Description: Towards the Mapping of Outdoor Human Tasks and Process Planning Activities to Artificial Indoor Manufacturing Environments*

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Article

Mapping Parallels between Outdoor Urban Environments and Indoor Manufacturing Environments

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Abstract: The concepts of "Smart Cities" and "Smart Manufacturing" are different data-driven domains, although both rely on intelligent information technology and data analysis. With the application of linked data and affordance-based approaches, both domains converge, paving the way for new and innovative viewpoints regarding the comparison of urban tasks with indoor manufacturing tasks. The present study builds on the work, who state that cities are scaled versions of each other, by extending this thesis towards indoor manufacturing environments. Based on their structure and complexity, these environments are considered to form ecosystems of their own, comparable to "small cities". This conceptual idea is demonstrated by examining the process of human problem-solving in transportation situations from both perspectives (i.e., city-level and manufacturing-level). In particular, the authors model tasks of human operators that are used to support transportation processes in indoor manufacturing environments based on affordances and spatial-temporal data. This paper introduces the fundamentals of the transformation process of outdoor tasks and process planning activities to indoor environments, particularly to semiconductor manufacturing environments. The idea is to examine the mapping of outdoor tasks and applications to indoor environments, and vice-versa, based on an example focusing on the autonomous transportation of production assets in a manufacturing environment. The approach is based on a spatial graph database, populated with an indoor navigation ontology and instances of indoor and outdoor objects. The results indicate that human problem-solving strategies can be applied to indoor manufacturing environments to support decision-making in autonomous transportation tasks.

Keywords: indoor manufacturing; linked data; urban versus manufacturing; smart manufacturing; smart transportation

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1. Introduction and Motivation

The concepts of "Smart Cities" and "Smart Manufacturing" are different data-driven domains, although both rely on intelligent information technology and data analysis. With the application of linked data and affordance-based approaches, both domains converge, paving the way for new and innovative viewpoints regarding the comparison of urban tasks with indoor manufacturing tasks. This also extends towards spatial task planning and urban human characteristics in the context of manufacturing environments. By mapping urban and human characteristics onto indoor manufacturing environments, and vice-versa, the authors will demonstrate the occurring common denominators. Specifically, the article discusses the mapping of human task planning activities to the indoor manufacturing environment of a semiconductor company and the application of the suggested methodology to the example of an autonomous indoor wayfinding problem. The present study builds on [1], who state that cities are scaled versions of each other. To successfully achieve this mapping, the authors base their comparison on manufacturing-related data and the spatial-temporal dimension of production processes and, thus, manufacturing data [2,3].

Urban data and the data of cities are strongly intertwined by space and time [4]. Therefore, the authors assume the presence of similar patterns in manufacturing environments and the associated data. Furthermore, references [1,5] point out that cities represent versions of each other at different levels of scale [6]—i.e., cities are "mini-versions" of each other. Thus, the authors formulate the hypothesis that any manufacturing environment may be regarded as a "mini-version" of an urban environment as a prerequisite in this paper. This hypothesis is based on the commonalities between the indoor manufacturing environment and the elements of a city.

To support the hypothesis, similarities of both environments are highlighted by the authors as follows: spaces for movement exist as corridors indoors and as streets/sidewalks outdoors. Further, each manufacturing device needs to be supplied with processing assets, thereby sharing commonalities with industrial companies and/or households that get their raw materials and groceries delivered. Indoor manufacturing environments may exhibit a multi-modal transportation network connecting human transportation and automated transportation systems comparable to multi-modal public transportation networks or supply chains. Further analogies between urban and manufacturing environments exist in terms of potential barriers, whereby urban barriers affecting traffic or pedestrians are comparable to barriers in production negatively impinging on transportation and production flows. Thus, such barriers cause detours and have an impact on pathways in urban and manufacturing environments alike. In this specific indoor context, humans represent key-stakeholders regarding transportation, quality, and efficiency, as they serve as a common interface, physically "connecting" machines and assets, including their transportation.

When mapping human behavioral tasks and process planning onto indoor manufacturing environments, production assets, personnel, and machines are key elements that need to be taken into account. Similar to urban environments, human individuals execute tasks that are based on relationships, properties, and affordances associated with other human individuals, objects, and the environment they reside in. To complete these tasks, human individuals visit locations and perform specific subtasks in a certain order. This specific order is the result of case-based planning [7] and problem decomposition into smaller subtasks [8,9]. Similar to urban environments, any individual acting within an indoor manufacturing environment has to perform transportation and processing tasks in a given order based on pre-defined workflows. In addition, due to occurring immediate necessities such as production problems, machine breakdowns, or moving production targets, decisions have to be made in a timely fashion. Individuals have to satisfy needs and tasks, regardless of their local context (i.e., urban versus manufacturing environment). Therefore, they have to search for appropriate locations in which to satisfy their needs/tasks prior to starting their actual journey or transportation operation, which is not only based on physical distance [6]. Thus, the line of argumentation is that the theory of general problem-solving and task and process planning can be applied to manufacturing environments.

The indoor manufacturing environment at hand—serving as a test area for the present study—is a semiconductor manufacturing environment. There, each produced production asset passes hundreds of production steps, which are not aligned on a conveyor belt due to the high variety of product types in conjunction with a dynamic manufacturing environment. The latter is a result of varying customer demand, which alters the mix of product types to be manufactured. Furthermore, production processes are globally distributed over several manufacturing sites. In addition, each production facility consists of several manufacturing halls.

The presented indoor manufacturing environment is modeled as an indoor navigation ontology by [10]. This indoor navigation ontology describes the indoor production space itself, as well as inherent navigational tasks; the authors combine historical manufacturing data with the indoor space and its peculiarities [10,11]. Further information can be inferred using the ontology, as it reveals links, specific relations, and a contextual perspective of each object under review [12]. According to [13], graphs, in particular in the form of the Resource Description Framework (RDF), are useful for connecting datasets with typed links, opening up new opportunities for knowledge extraction. Consequently, the authors introduce a graph database, comprising a semantic knowledge description of manufacturing-relevant data, together with their respective spatial and temporal dimension [14]. The graph database is the foundation for identifying "optimal" transportation routes for human individuals, regarding manufacturing processes, product quality, and efficiency. It includes a transportation optimization, similar to any urban navigation and wayfinding—whereby the transportation in the production facility is done by humans.

The research question of this paper can be summarized as "Can urban human tasks and process planning strategies be mapped onto an indoor manufacturing environment?" This comparison intends to support transportation processes for manufacturing purposes by exploiting graph-oriented databases and ontologies for navigation purposes". Thus, the authors focus on the comparison of urban tasks and processes with indoor manufacturing "activities" to gain an understanding of the solution strategy of task decomposition. They apply this general approach in the context of manufacturing environments, coupled with an affordance-based routing approach to support transportation processes in indoor spaces. The authors do not intend to elaborate on the navigation algorithm, as this will be outlined in a forthcoming paper [15]. Here, the authors present the idea of applying the solution strategy of decomposition for solving tasks in outdoor spaces to an indoor manufacturing environment. In literature, a number of navigation solutions for indoor environments exist; no publication combines task and trip planning based on an ontology for indoor purposes. Thus, we restrict ourselves to the description of the problem-solving methodology that involves the decomposition of complex problems. This approach is intended to reduce the computational complexity of the problems—i.e., task and trip planning—in the manufacturing environment, in order to handle them with a reasonable computational effort. The motivation behind and the benefit of the comparison are based on the mapping of applications from outdoor to indoor environments, and vice-versa, ensuring the reusability of applications. An additional benefit is based on the concept of affordances, as a new ruleset is necessary for re-use.

The structure of the paper is as follows: Section 2 highlights related work and literature, followed by the description of urban and manufacturing process characteristics in Section 3. Section 4 focuses on the modeling of transportation tasks. Affordance-based navigation based on graphs is described in Section 5, concentrating on supporting autonomous navigation of production assets in indoor manufacturing environments by decomposing tasks into subtasks. The paper closes with the discussion and conclusion.

2. Related Work

This section is dedicated to related literature that contributes to the fields of expertise covered in this paper. Hence, the authors focus on task and process planning characteristics, manufacturing environments and processes, indoor geography, indoor navigation tasks, and the theory of affordances. Moreover, emerging topics such as linked data and semantics, and sensor approaches in urban and manufacturing environments, are covered.

During the past decades, data collecting techniques—indoor and outdoor—have been used in a pervasive manner (i.e., environmental sensors, remote-sensing techniques, smartphones), creating vast amounts of spatial data. These data are of interest for numerous scientific domains and may be helpful for gaining new knowledge, i.e., in ecology or environmental engineering [16,17]. The amount of data produced and processed has triggered a paradigm shift from data-scarce to data-rich geography [18]. This paradigm shift towards big spatial data requires an appropriate new set of "tools" that enable cloud-based collaborative computing and data-intense knowledge discovery [19].

The fact that an average person resides inside buildings 90% of the time has triggered numerous research activities regarding the application of Geographic Information Science (GIScience) in indoor environments [20]. Early research work on indoor modeling and pathfinding includes [21,22], where an airport serves as an example for agent-based indoor pathfinding. To model indoor spaces, several approaches exist that range from reducing the indoor space to a graph (e.g., [23,24]) to creating building information models (e.g., [25]). Worboys [26] provides a comprehensive list of current approaches. Among others, authors in [10,27] employed ontologies to model indoor space. In detail, authors in [10] applied such an ontology modeling approach to a complex indoor manufacturing environment. Additionally, the authors of [28] have proposed that taking the spatial and temporal dimensions into account can support decision-making processes in manufacturing environments, thus supporting smart manufacturing.

For any manufacturer, productivity and efficiency are the key to being successful on the market. To support decision-making in indoor manufacturing environments, smart manufacturing is one of the main research fields facilitating competitiveness [2]. Therefore, most manufacturing companies collect data from manufacturing processes with explicit and implicit spatial-temporal references to enable data analysis and visualization. By applying methods of geo-visual analytics, humans can be supported in identifying patterns within the given data [29,30]. In addition, near real-time visualization of manufacturing data is of interest due to the emergence of wearable devices for employees and managers [31]. Identifying spatial-temporal patterns may help to develop optimization strategies and technologies to increase manufacturing efficiency, i.e., cost savings and increased performance [32].

Human processes, tasks, and the planning thereof are research issues in cognitive science and in GIScience. The planning of processes and tasks is related to this area of problem-solving [33]. To solve a problem, past experiences can be utilized [7]. Notable are the publications of [8,9,34], who elaborate on the processes behind problem-solving. A rather formal description of the cognitive process of human problem-solving is presented in [35]. Raubal and Worboys [21,22] describe the problem of pathfinding in indoor environments, which is strongly related to cognitive science. Abdalla et al. [36–38] analyze trip planning, decision-making, and influences on spatial-temporal personal information management.

The theory of affordances itself is presented by [39] (p. 127) as the environmental offer for "the animal, what it provides or furnishes, whether good or ill". The theory of affordances has been widely applied in GIScience, e.g., allowing agents to interpret environmental objects for the purpose of wayfinding [22]. The theory of affordances is a potential solution for human task planning and wayfinding, demonstrated by [40], who published a solution to calculate spatial suitability for wayfinding based on affordances. The manufacturing environment at hand considers affordances of the production asset, the indoor space—network—and the environment—blockings, contaminations, quality—with respect to the context of the production asset—i.e., the position in the indoor space and the next processing step.

3. Process Characteristics and Problem-Solving in Urban and Manufacturing Environments

This section highlights characteristics of problem-solving in urban environments. Specifically, the authors demonstrate that problem-solving is a form of decomposition of a given task into several subtasks. Furthermore, the execution of these tasks is related to space. The authors show that indoor manufacturing environments share similar characteristics with urban spaces.

Problem-solving, in general, relates to the planning of tasks and the determination of their particular order to fulfil a certain goal. The paper [33] (p. 284) presents a problem-solving definition, as "cognitive processing directed at transforming a given situation into a goal situation when no obvious method of solution is available to the problem solver". Problems arise in an ill-defined and well-defined manner. Eysneck and Keane [34] state that well-defined problems have a given initial state and a well-defined set of rules to generate a solution. An ill-defined problem has a potentially infinite number of possible solutions. To solve a given problem, humans tend to make use of past experiences. This strategy is known as case-based planning [7]. Higher levels of experience lead to increased effectiveness at problem-solving. Furthermore, authors in [8,9] state that humans tend to decompose problems into several sub-problems. Each sub-problem is solved individually, and the respective solutions are then aggregated to generate the solution to the overarching problems. Similar decomposition approaches regarding task planning have existed in GIScience since the early 1990s. Timpf et al. [41] describe a conceptual model of human navigation for the US interstate highway network. Their research work distinguishes three different levels on which decisions about navigation problems are made, i.e., the planning level, the instructional level, and the driver level. Abdalla and Frank [38] presented a combination of trip- and task planning, based on the example of "how to get a passport". In their paper, they decompose the overarching problem of "getting a passport" into sub-problems or tasks that have to be solved individually in a certain order.

Additionally, references [36–38,41] show that the decomposition of spatial-temporal problems is also a matter of scale. This can be justified by the work of [41], where sub-problems (i.e., different levels) are modeled with a finer "resolution" of the representation of the universe of discourse. On the planning level, only highways, places, and interchanges are present, whereas on the driver level, the highways and interchanges are modeled with high detail (see Figure 1). By taking a closer look at cities and the processes in a city, references [1,5] argue that there are universal properties of cities, regardless of their size and cultural and historical differences. Noulas et al. [6] (p. 8) describe this as follows:

> *"[...] universal properties in cities around the globe [...] where cities have been shown to be scaled versions of each other, despite their cultural and historical differences."*

Thus, it can be concluded that the size of the universe of discourse under review does not matter when examining general behavior and approaches to solve a given problem. Hence, the manufacturing environment under review in this paper can be regarded as a small "urban environment" where people try to fulfil tasks with respect to the given problem.

Figure 1. Representation of a highway interstate interchange (left) and the highway (right) at different scales (coarse scale in (**a**) and fine-grained scale in (**b**)) (adapted from [41]).

To justify the presented approach that the behavior of people in indoor and urban environments is similar regarding problem-solving—e.g., navigation—the authors utilize the concept of geodesign [42]. Goodchild [43] (p. 9) describes geodesign as follows:

> *"[...] geodesign is concerned with manipulating those forms and intervening in these processes to achieve specific objectives."*

This indicates that any urban environment may be regarded as constructed and controlled, since humans impact the urban environment. In addition, the authors argue that problem-solving and the execution of tasks in urban and indoor environments share a high level of similarity. To demonstrate that task and process planning cannot be separated from each other—with respect to the spatial dimension (e.g., trip planning)—they refer to [6] (p. 2):

> *"More importantly, our analysis is in favor of the concept of intervening opportunities rather than gravity models, thus suggesting that trip making is not explicitly dependent on physical distance*

but on the accessibility of resources satisfying the objective of the trip. Individuals thus differ from random walkers in exploring physical space because of the motives driving their mobility."

Thus, Noulas, A., et al. [6] strengthen the argument that the planning of tasks in an environment is related to trip planning (in this context, used as a specific process to reach a given objective). This is also justifiable according to the work of [38], who combine trip and task planning—where processes are planned accordingly.

In the field of smart mobility, further analogies to smart manufacturing have been described [44,45]. Smart mobility can be regarded as a collection of coordinated activities aimed at improving efficiency, effectiveness, and environmental sustainability [46]. In addition, smart mobility generates an impact through the combination of technology, existing physical and technical capabilities, and by considering human and social needs [47]. Hence, we conclude that smart mobility present in urban environments shares a certain similarity to indoor manufacturing processes. In both cases, intelligent planning to support humans in decision-making seems to be the essence. Nevertheless, the generation of "optimal" solutions is complex, as the problems are mostly computationally hard to solve and require the integration of human behavior and the social component.

In this section, we have elaborated on the similarity of urban and manufacturing environments in a very generic way. Nevertheless, it is worth pointing out that there are also some differences between urban spaces—i.e., smart cities—and smart manufacturing environments. This is especially true in the case of spatial/urban planning, where bottom-up participation replaces traditional top-down approaches [48,49]. The shift to bottom-up participation opens new possibilities for, e.g., the web paradigms that enable the sharing of data and new interaction modes. In addition to sensors physically present in the city, the citizens should at least share their opinion for this bottom-up participation. In smart manufacturing environments, sensors are present—similar to smart cities—but the design and planning of the working space follow a top-down approach. This is especially true for semiconductor companies, as cleanroom space is expensive to construct and maintain, resulting in "crowded" indoor spaces optimized for manufacturing purposes.

4. Transportation Tasks: From General Principles to Production Assets

Transportation tasks are encountered in urban areas and in manufacturing environments. In a manufacturing environment, humans execute transportation tasks, which represent the link between production machinery and production assets. Similar to manufacturing environments, humans link the commodities to be transported and their targets in the urban environment. Therefore, "smart transportation" may increase efficiency, quality, and effectivity of the processes.

This section is a follow-up of the argumentation presented in Section 3 and concludes that an indoor manufacturing environment can be described as a "mini-version" of a city, according to [1,5]. To illustrate the idea of decomposing an overall objective (problem) into specific tasks, a general design of a transportation task is depicted in Figure 2 and described in Section 4.1. Subsequently, a more detailed comparison of a transportation task in urban and in manufacturing environments is presented in Section 4.2.

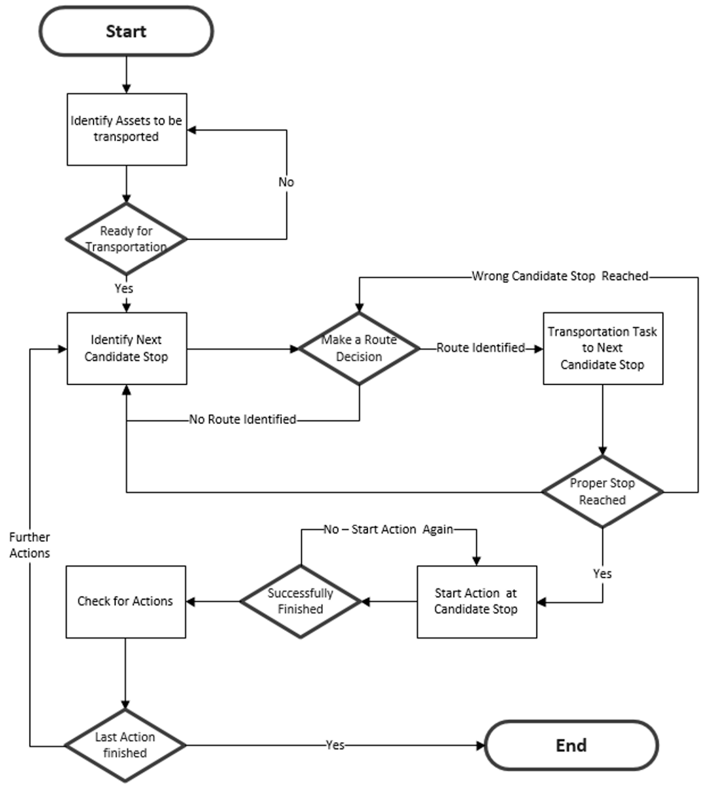

Figure 2. Smart transportation process in a manufacturing environment. The general process is broken down into several sub-processes including the actions to be performed at certain stops on the route (e.g., pickup or delivery of a production asset).

4.1. Transportation and Associated Subtasks

An example of a "smart transportation" task of any asset is depicted in Figure 2. Here, the task is divided into ten main steps that have to be considered, including required process loops:

(1) **Identify Asset to be Transported** (*Process*): At the beginning of each transportation task, it is necessary to identify the (set of) objects that (has) have to be transported.
(2) **Ready for Transportation** (*Decision*): After the identification process of an asset or several assets, it is necessary to decide whether the human individual and the assets are ready for the transportation task. In the case of the asset, the human has to decide whether the asset is transportable.
(3) **Identify Next Candidate Stop** (*Process*): Before the transportation task can be executed, the next candidate stop has to be identified. The identification of the next candidate stop is a process where we determine/calculate the next delivery location of the commodity (-ies) that are currently transported. The identification is dependent on the current location of the transportation device, the assets and their next manufacturing processes, and the location of available manufacturing equipment capable of carrying out the loaded asset(s)' further processes.
(4) **Make a Route Decision** (*Decision*): Because the next candidate stop is known and the asset/assets are transportable a route decision can be made—until now by the human operator. Therefore, the human has to consider the environment, asset information, and walkable ways to the candidate

stop. If no decision regarding a route can be made, the process takes a step back to identify a possible candidate stop.

(5) **Transportation Task to Next Candidate Stop** (*Process*): This process focuses on the actual transportation task of the human who needs to follow a certain route. Thereby, navigation events such as turning left or right are necessary.

(6) **Proper Stop Reached** (*Decision*): Once the transportation task finishes it has to be validated that the right candidate stop is reached and the planned action (i.e., manufacturing process) can be performed. In any other case, there is a fall back to either the identification of a "new" next candidate stop or a "new" route decision.

(7) **Start Action at Candidate Stop** (*Process*): This represents the action that is performed at a candidate stop, e.g., the processing of a commodity using manufacturing equipment or the delivery of assets to shelves.

(8) **Successfully Finished** (*Decision*): After the planned action has been performed at the candidate stop, it has to be checked whether the interaction was successful. If the interaction was successfully finished, the general process can be continued. Otherwise, the action has to be started again.

(9) **Check for Actions** (*Process*): As there is a pre-defined sequence of actions/tasks, this process determines whether there are further actions in the sequence.

(10) **Last Action finished** (*Decision*): Finally, a decision has to be made as to whether there is a successor action defined for the asset or not. In case of a successor action in the sequence, the loop is closed, and the transportation task starts over with the identification of the next candidate stop. Otherwise, this transportation task has successfully finished.

4.2. Comparison of an Urban and a Manufacturing Task

In the following section, the authors compare subtasks—as described in Section 4.1—with transportation subtasks in different contexts. Table 1 shows a direct comparison between general transportation subtasks and more specific transportation subtasks—one within a manufacturing environment and the other within an urban environment. Table 1 provides an example for urban transportation via a parcel:

Table 1. Comparison of the defined general tasks and specialized tasks (manufacturing versus urban).

"Smart Transportation" Task		Manufacturing Transportation		Parcel Service	
General Design	Identify objects to be transported	**Manufacturing Environment**	Identify the production asset for a transportation task	**Urban Environment**	Identification of parcels for transportation task
	Ready for transportation		Ready for transportation—trolley is loaded		Ready for transportation—car/truck is loaded
	Identify next candidate stop		Identify next processing equipment–dispatching list		Identify next delivery address—i.e., order of customers due to time, parcel conditions . . .
	Make route decision		Make route decision on production assets affordances		Make route decision on vehicle and parcels' affordances (traffic, dangerous goods, tolls, . . .)
	Transportation task to next candidate stop		Transportation task to next processing equipment		Transportation task to the next delivery address/customer
	Proper stop reached		Proper stop reached		Proper stop reached
	Start action at candidate stop		Start processing at the reached equipment		Start interaction with customer—deliver parcel + confirmation via signature
	Successfully finished		Processing successfully finished		Parcel successfully delivered to customer
	Check for actions		Check for further processing steps		Check if there are further parcels for delivering
	Last action finished		Last processing step finished		Last package delivered

5. Graph Databases to Support Transportation Tasks in Indoor Manufacturing Environments for Humans Based on Affordances

This section elaborates on a digital representation of the universe of discourse that supports autonomous transportation processes in an indoor manufacturing environment. Thus, the authors highlight a graph database that includes an amended version of the indoor navigation ontology developed by [10] and a set of manufacturing data. They present an affordance-based routing approach that is capable of decomposing complex transportation problems into several subtasks based on the implemented ontology, the environment, and the properties of the object.

5.1. Graph-Based Spatial-Temporal Representation of the Universe of Discourse

This section discusses the representation of the indoor space, the semantic description thereof, the navigation ontology, and the manufacturing data that is integrated into a spatial graph database. A general introduction to graph databases and their fundamental concepts are presented in, e.g., [50], whereas the successful combination of ontologies and graph databases in GIScience is described in [51]. In general, a graph database is a database management system that is capable of creating, reading, updating, and deleting data in the form of graphs. Graphs are a collection of vertices and edges that correspond to real-world entities and the relationships between them. In graphs, entities are modeled as vertices and relationships as edges. This allows real-world scenarios such as supply chains, road networks, or the medical history of populations (see, e.g., [52]) to be modeled in terms of graphs. Graph databases have become very popular due to their suitability for representing social networks and are thus utilized in systems such as Facebook (Open Graph) or Google (Knowledge Graph) (see [52]).

The graph database in this paper contains historical data and data necessary for current manufacturing purposes. In general, it combines several distributed data sources—such as sensors or other databases—and intends to establish a linked data approach. Through this linked data approach, which is based on graphs and relationships, a new contextual perspective is added to the data [12]. Therefore, a graph model is developed including a semantic description (i.e., an ontology) of the indoor space and the navigation processes [10]. Additionally, the graph model also incorporates aspects of space and time [14].

In order to store manufacturing data in the graph database, the authors extend the data model introduced by the ontology by [10]. In the remainder of this article, the ontology developed by [10] is denoted as IndoorOntology::Production. This data model comprises historical information and attributive data, which are stored as a trajectory of the production asset, together with data on the next processing steps. Based on this, Schabus, S., et al. [53] developed a spatially linked manufacturing data approach with the production asset as the main entity in the manufacturing environment. Therefore, the manufacturing environment involves historical information—like the trajectory and the performed production steps—and the future manufacturing steps. The production asset links the trajectory, equipment, and sensor data of processes along a production chain with the future production steps (i.e., the so-called operations "aligned" on a route) and suitable equipment for each operation [53].

According to [53], Figure 3 shows the historical information of a production asset. The blue circle denotes an abstract class of the IndoorOntology: Production. The relationship "*hasIndividual*" links the abstract class with the individuals—i.e., each production asset. The nodes on the right side represent attributes describing the production asset and are linked to the asset via the relationship "*isPropertyOf*". A processed production asset has already executed processes—denoted in red—that are connected via the relationship "*hasExecutedProcess*". Furthermore, any production asset has a trajectory linked via "*hasTrajectory*", and each trajectory is linked to several tracked positions via "*hasAssetPosition*", visible at the bottom of Figure 3. The sequence of tracked positions is defined via the relationship "*nextPosition*". To keep the linkage to future manufacturing processes, each production asset has the relationship "*hasRoute*", which is marked with a green bubble. In addition, each route has several operations that need to be carried out in a pre-defined order. These operations are linked with the route via the relationship "*hasOperation*", and the pre-defined sequence of operations is kept via the relationship "*nextOperation*". These relationships are not depicted in Figure 3 but are described in [53]. One operation, which is modeled in the graph database [53], can be performed on several processing devices and vice-versa.

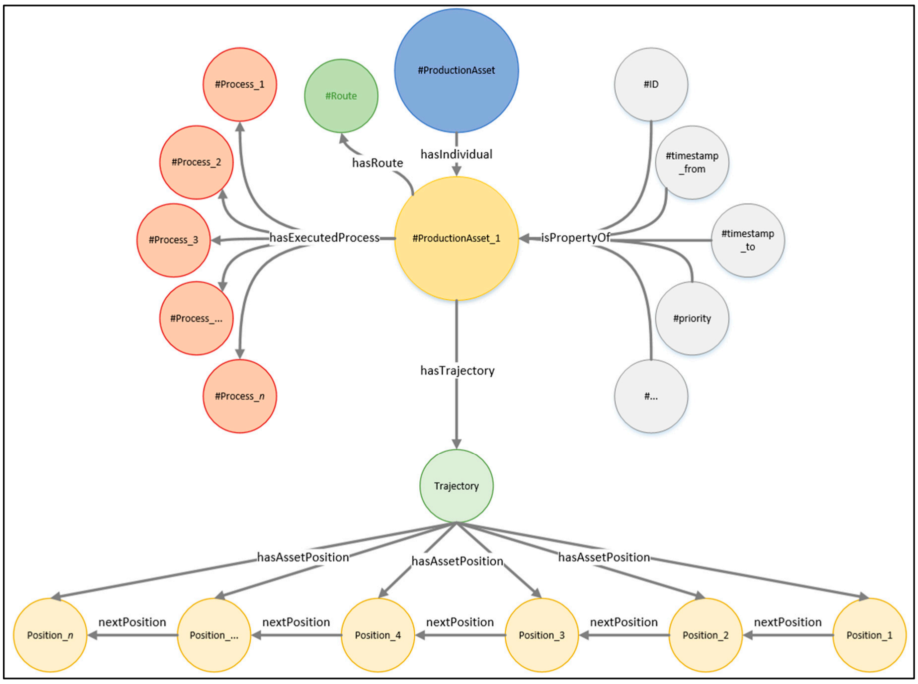

Figure 3. Visualization of the historical information of a production asset. Each circle represents an information artefact in the graph database that is connected to other information artefacts via relationships. A tagged arrow represents a relationship between two information artefacts. The blue circle denotes an abstract class, ProductionAsset, with its instance depicted by a yellow circle. Attached to the instance of the ProductionAsset are the executed processes, the trajectory with the sequence of positions, and a number of properties, which are represented as grey circles. The route is the collection of future production processes to be carried out [53].

According to [10], production assets move along the corridors (center lines) of the manufacturing hall that are comparable to streets in the urban environment displayed in Figure 4. Thus, a network model with nodes and edges is stored in the graph database to reflect these circumstances and to support indoor navigation. Combining future production operations for production assets, equipment information, and the indoor environment opens up the opportunity to (a) analyze historical events and processes in the manufacturing environment and (b) support the autonomous routing of production assets by breaking down the production process into smaller subtasks. The routing, based on the indoor ontology and, thus, affordances, is the subject of Section 5.2.

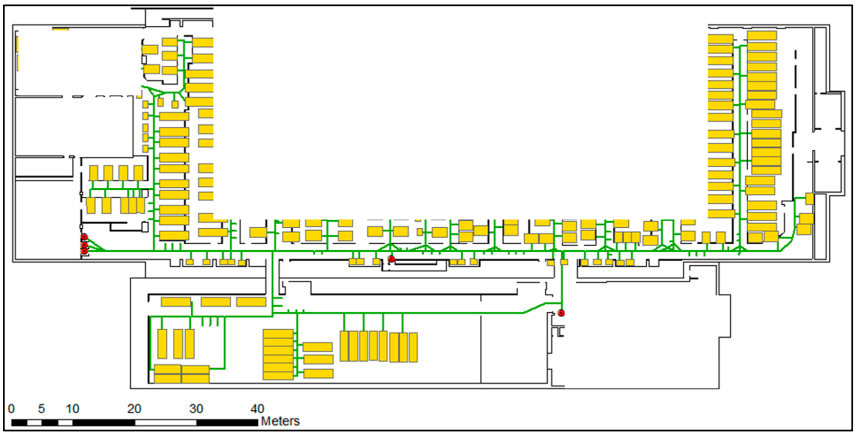

Figure 4. An indoor space layout of the manufacturing environment. Yellow rectangles represent devices in the clean room, and red dots represent transfer nodes. The green lines represent the traversable indoor network. The white spaces intentionally disguise the complete production layout (adapted from [10]).

5.2. 'Optimal' Indoor Transportation Routes Supported by an Affordance-Based Approach

Based on the graph database model described in Section 5.1, the authors elaborate on an affordance-based navigation solution for indoor manufacturing environments, which breaks down the general problem into several subtasks, following the task decomposition for problem-solving [8,9]. The overall algorithm follows the process depicted in Figure 2, with the identification of objects, the proof of the objects' readiness for transportation, the identification of the next candidate stop, the route decision itself, and, finally, the execution of tasks to check if the process was successful and if further tasks or subtasks exist. The algorithm is based on an indoor navigation ontology describing the indoor environment—i.e., the context—and the navigation task itself, which is the basis for the definition of the entities and affordances of each object in the cleanroom, stored in the graph database.

To calculate an "optimal" transportation route, the transportation task is divided into smaller subtasks, referring to the task decomposition for problem-solving [8]. The separation takes place because a large or complex task is not automatically solvable. Therefore, the line of argumentation leads to the decomposition of a large single task into smaller/atomic tasks that can then be solved, processed, and automatically compared to the respective affordances.

Each small/atomic task is consecutively processed based on the affordances offered by each entity in the manufacturing environment. According to [40], atomic tasks can be compared to affordances, which define the spatial suitability of an entity for a given task. Thus, processing the affordances answer the questions of where and how a decomposed task is "suitable", i.e., the processing of an asset, or changing the floor level.

The implemented concept proves the correlation between tasks, affordances, and the environment based on a route decision task. To find a production asset's route from one manufacturing device to the next, a decision has to be made about which edges the route should traverse. Routes, including their affordances, can be identified using a graph-based network stored in the graph database. Routes may include elevators or stairs, especially when an action like "change floor level" is necessary. Both basically afford the action of "transportation" and changing the floor level. Whereby, when processing the affordances and the suitability, the elevator achieves a much better score than the stairs with respect to safety and quality based on a much higher risk of damaging the silicon wafers through a shock when walking down the stairs.

To focus on the applied route decision task outlined in Section 4.1, we decompose the routing task into subtasks to enable decision-making by robots or simply to support human transportation in manufacturing environments. The approach is based on the affordance-based routing concept highlighted in [10]. To visually express the optimal transportation route, Figure 5 shows the results of a "make route decision" operation with the current position of an asset as the starting point (marked by a green point) and a defined target (marked by a red point). In other cases, the target point is provided by another sub-task ("process operation X") and an entity that offers the processing of the corresponding operation. For this example, the two identified candidate routes are visualized as a red and a green line. As can be seen, the shortest path would be the red dashed line, which is not the optimal path as there is an uneven floor leading to concussions of the production asset, which can be detected by acceleration sensors and-/or personal observations by human operators. In this specific example, the solid green line represents the optimal path for this specific route decision for the asset, avoiding possible damage through concussions on the shortest path. The unevenness may negatively influence the quality of this asset type, which is considered when calculating the suitability of the route. Hence, a longer transportation route may be regarded as optimal.

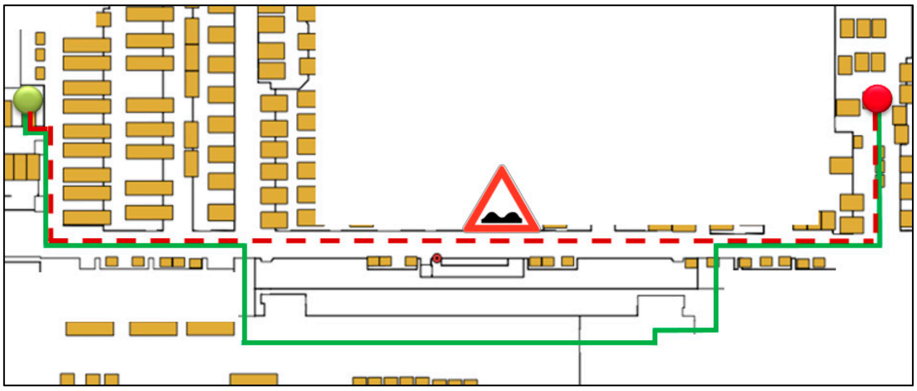

Figure 5. Visualization of the task "Make Route Decision" resulting in two visualized candidate routes and the highlighted optimal route of these two candidate routes. The smart transportation task starts at the green point on the left side and goes to the red point on the right side. The two possible candidate routes are identified as green and red lines. For this specific route decision, concussions affecting one candidate route—visualized in red—are detected by sensors or personal observations by human operators. Therefore, the optimal route is the solid green line, which is longer than the red one, but not optimal in terms of quality assurance.

6. Discussion and Conclusions

This paper elaborates on an approach to map characteristics of urban human tasks and process planning onto an indoor manufacturing environment. In detail, a general transportation task is analyzed and compared to a transportation process in a manufacturing environment. In addition, a graph database is implemented and utilized to calculate "optimal" transportation routes with respect to the contextual necessities of a production asset. This is done by integrating contextual data of the indoor environment and by exploiting an affordance-based routing approach.

In the paper, we focus on the transition of the problem-solving strategy—i.e., the decomposition of complex tasks—to an indoor manufacturing environment. The research contribution manifests itself in the combination of task and trip planning that is fully based on an indoor ontology and semantically enriched manufacturing data. Contemporary papers present navigation approaches for indoor spaces, focusing on getting from a starting point to a given target. In manufacturing environments, operators or assets have to fulfil tasks in order to finalize products so that these are ready to be shipped to the customers. As the production site has to fulfil volatile consumer demands, manufacturing processes are not aligned on a conveyor belt but are mostly geographically dispersed over the production halls. This requires a complex decision-making process, as both the target and the path need to be determined individually for each asset while considering quality standards. Quality standards are defined on the basis of production asset types present in the production line (usually several hundred).

The paper highlights relevant approaches to human problem-solving—mainly decomposition approaches. Decomposition can help to break down a complex task into smaller tasks that can be solved more easily. Here, we attempt to apply decomposition to a specific manufacturing environment—semiconductor manufacturing. The results should provide the theoretical basis to develop an algorithm for an affordance-based navigation solution for production assets. The navigation algorithm should include both task and trip planning in order to support the autonomous transportation of assets in an indoor manufacturing plant.

The basis for the experiment presented in this paper is a graph database, supporting the concept of linked data, and an ontology, describing the indoor space and the navigation tasks. Affordances are intertwined with sensor data, which represent information on the environment. Furthermore, the developed concept supports the determination of an optimal path from a source to a target point in a manufacturing environment, where optimality refers to the affordances, the quality issues, and the context of the production asset. For a spatial or spatial-temporal analysis, historical information is stored in the graph database. These data can support case-based planning [7], which is based on historical experiences. This approach may contribute to the decomposition approach followed in this paper. Here, overall problems or tasks are decomposed into smaller subtasks that are solved in a given order [8,9].

Open issues that are not tackled in the paper are a performance analysis of the algorithm supporting the autonomous navigation of production assets and the impact of the algorithm on the "travel behavior" of production assets. The latter could be analyzed by an approach following geo-visual analytics or geostatistical methods, whereas a detailed performance analysis would require an analysis of the underlying algorithm in a mathematical manner and in-situ testing—see [15] for details. In the indoor environment under review, humans carry out transportation tasks, which leads to the necessity of communicating the recommendations of the system in a user-centered manner, utilizing theory and methods from the Human Computer Interaction. In addition, this paper focuses to a large degree on the similarities between manufacturing environments and urban environments. From a GIScience point of view, it would be interesting to look at both the similarities and differences between them and the implications, e.g., for modeling a manufacturing environment.

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Author Contributions: Stefan Schabus developed the proof-of-concept implementation, wrote the basic parts of Sections 4–6, contributed most parts of Sections 1–3 and contributed to the research design. Thomas J. Lampoltshammer contributed to Sections 1–3 and 5.1 (graph databases), and contributed to the research design. Johannes Scholz contributed to Sections 1–3, 5 and 6 and developed the research design together with Stefan Schabus and Thomas J. Lampoltshammer.

Conflicts of Interest: The authors declare no conflict of interest.

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Chapter 11

Towards an Affordance-Based Ad-Hoc Suitability Network for Indoor Manufacturing Transportation Processes

Transportation of production assets affects the production quality, efficiency and productivity. To therefore identify the optimal path, an ad-hoc suitability network is generated. This supports a just-in-time decision of the optimal path based on affordances. The author activities are described in detail in figure 11.1 (Scholz and Schabus, 2017).

<table>
<tr><td>Title:</td><td colspan="7">Towards an Affordance-Based Ad-Hoc Suitability Network for Indoor Manufacturing Transportation Processes</td></tr>
<tr><td>Authors:</td><td colspan="7">Johannes Scholz – Graz University of Technology, Institute of Geodesy, Research Group Geoinformation, Graz, Austria
Stefan Schabus – Infineon Technologies Austria AG, Villach Austria</td></tr>
<tr><td>Submission Info:
(Type, Conference,…)</td><td colspan="3">International Journal of Geo-Information, Special Issue “3D Indoor Modelling and Navigation” – Journal Publication</td><td>Published:
(year)</td><td>2017</td><td>Pages:</td><td>18</td></tr>
<tr><td>Reference:</td><td colspan="7">Scholz, J., & Schabus, S. (2017). Towards an Affordance-Based Ad-Hoc Suitability Network for Indoor Manufacturing Transportation Processes. ISPRS International Journal of Geo-Information - Special Issue 3D Indoor Modelling and Navigation, 6(9), 280</td></tr>
<tr><td colspan="8">Short Description of Authors Activities</td></tr>
<tr><td>Johannes Scholz:</td><td colspan="2">▪ Wrote mainly the manuscript together with Stefan Schabus
▪ Responsible for Author Correspondence</td><td>Stefan Schabus:
(Candidate)</td><td colspan="4">▪ Wrote the manuscript together with Johannes Scholz
▪ Implementation of the Algorithm and proof of concept
▪ Responsible for internal and external release processes</td></tr>
<tr><td colspan="8">Detailed Description of PhD (Stefan Schabus) - Activities</td></tr>
<tr><td colspan="8">▪ The candidate supported the writing of the manuscript with the main focus on:
    ▪ Analysis of the Algorithm and the Proof of concept of an optimal path
    ▪ Supported the writing of the introduction and relevant work

▪ The structure of the journal was developed forehand by both authors as well as the development of the algorithmic approach.

▪ Implementation of the proof of concept and the optimal path use-case of the Affordance-Based Ad-Hoc Suitability Network
    ▪ Includes the Analysis of the implemented algorithm

▪ Management of internal release processes of the production company and external release processes of the publisher</td></tr>
</table>

Figure 11.1: *Author Activity Description: Towards an Affordance-Based Ad-Hoc Suitability Network for Autonomous Indoor Manufacturing Transport Processes*

International Journal of
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MDPI

Article

Towards an Affordance-Based Ad-Hoc Suitability Network for Indoor Manufacturing Transportation Processes

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Abstract: In manufacturing companies, productivity and efficiency are the main priorities, besides an emphasis on quality issues. The outcome of this research contributes to increasing production quality and efficiency in manufacturing. The article deals with indoor manufacturing environments and the transportation processes of production assets—referred to as smart transportation. The authors modelled the objects present in the indoor manufacturing environment with ontologies including their affordances and spatial suitability. To support flexible production and dynamic transportation processes have to be tailored towards the 'needs' of the production asset. Hence, the authors propose an approach utilizing an ad-hoc suitability network to support the "optimal" path computation for transportation processes. The objective is to generate a graph for routing purposes for each individual production asset, with respect to the affordances of the indoor space for each production asset, and measurements of a sensor network. The generation of the graph follows an ad-hoc strategy, in two ways. First, the indoor navigation graph is created exactly when a path needs to be found—when a production asset shall be transported to the next manufacturing step. Secondly, the transportation necessities of each production asset, as well as any disturbances present in the environment, are taken into account at the time of the path calculation. The novelty of this approach is that the development of the navigation graph—including the weights—is done with affordances, which are based on an ontology. To realize the approach, the authors developed a linked data approach based on manufacturing data and on an application ontology, linking the indoor manufacturing environment and a graph-based network. The linked data approach is finally implemented as a spatial graph database containing walkable corridors, production equipment, assets and a sensor network. The results show the optimal path for transportation processes with respect to affordances of the indoor manufacturing environments. An evaluation of the computational complexity shows that the affordance-based ad-hoc graphs are thinner and thus reduce the computational complexity of shortest path calculations. Hence, we conclude that an affordance-based approach can help to decrease computational efforts for calculating "optimal" paths for transportation purposes.

Keywords: indoor manufacturing; smart transportation; affordance-based navigation; linked manufacturing data; spatial graph database

1. Introduction and Motivation

The interest in indoor geography-related research is increasing, especially as humans spend almost 90% of their daily time inside buildings [1,2]. In fact, most manufacturing processes take place in indoor spaces. In this paper we focus on semiconductor manufacturing, that requires an indoor cleanroom environment for the manufacturing process chain. Currently, there are a number of initiatives subsumed under the umbrella of smart manufacturing or Industry 4.0 that strive to increase the efficiency of manufacturing processes. In this context, Geoinformation may contribute in terms of modeling indoor space [3] or decision support for manufacturing purposes [4–6].

The universe of discourse (UoD) under review in this paper is a complex and highly flexible manufacturing environment of a semiconductor company, described in detail by [3,4]. To illustrate the complexity in the manufacturing line, there are several hundred production steps necessary to manufacture a single microchip. Hence, the time to finish a product varies from several days to several weeks [3,4]. Furthermore, several hundred different products are manufactured at the same time in the cleanroom. The equipment is spatially distributed across the manufacturing site, as the production is not aligned on a conveyor belt. One single production operation may be executed on several equipment. In addition, several thousand production assets are present in the factory in different degrees of completion. The layout of the cleanroom changes frequently, due to maintenance tasks, dismounting and/or installation of manufacturing equipment.

Currently, humans mainly do the transportation of production assets. Operators load production assets on trolleys and deliver each item to the next manufacturing step—which is dependent on the product type. In order, to increase the efficiency of the manufacturing environment in terms of Industry 4.0, the overarching goal is the transportation of production asset by either an autonomous transportation or by an autonomous assistance of humans. Because each product class, present in the production line, has specific requirements on the chosen transportation route in conjunction with constant changes in the indoor layout, there is a need for a dynamic, context-sensitive transportation planning (see Figure 1).

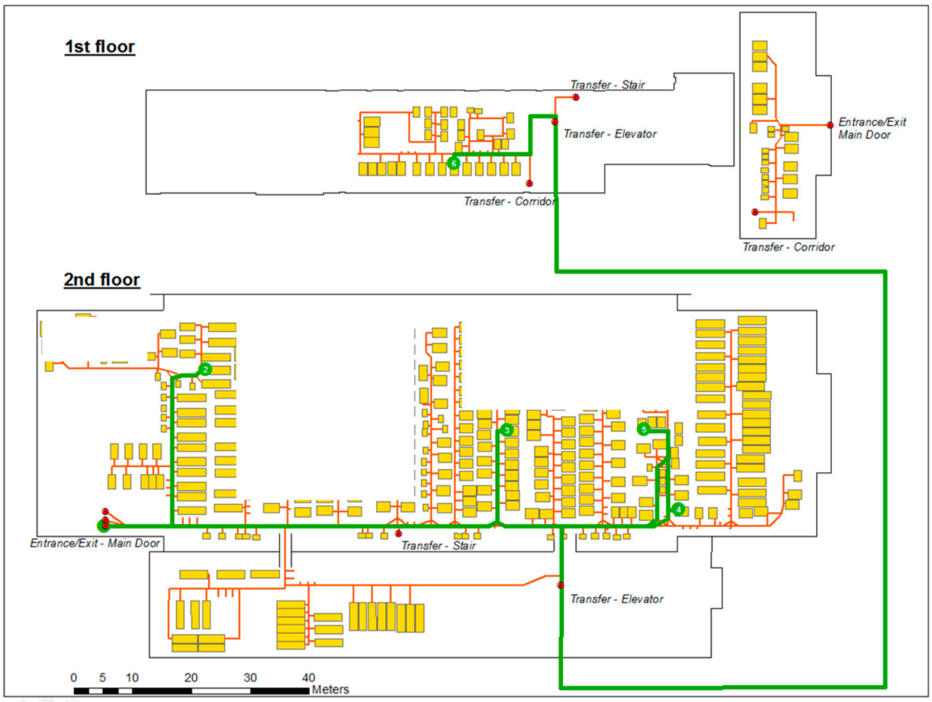


Figure 1. Prototypical application of an affordance-based path calculation for a given production asset (from [3]). The calculated path of a production asset, from entering the production line at node (1) and undergoing several manufacturing steps (nodes 2–6).

In order to support context-sensitive transportation planning in an indoor environment an ontology is employed [3], that provides contextual information, linkages, and defined relations of the objects under review [7]. Based on the ontology, large volumes of spatial-temporal data originating from multiple data sources are combined, and analyzed to describe the production assets 'needs'.

Transportation planning and optimization in the context of this paper does not necessarily mean to minimize the physical transportation distance. Destinations—i.e., manufacturing equipment—and the path itself have to satisfy certain needs depending on the production asset at hand [8,9]. Based on the needs, we can calculate the suitability of possible transportation paths in the indoor environment. In this paper, we utilize the concept of affordances to calculate the spatial suitability—similar to that demonstrated by the authors of [3]. The term affordance is defined by [10,11] as action possibilities perceived in a direct and immediate way. Additionally, the authors of [12] extended the theory of affordances to model spatial suitability. Furthermore, we follow an ad-hoc approach for the generation of the navigation graph. The ad-hoc aspect refers to the fact that a navigation graph is calculated for each production asset individually, when a path to the next manufacturing step is required. The calculation of the navigation graph and subsequently the "optimal" path adheres to the spatial suitability and relevant disturbances in the indoor environment at the time of the calculation—detected by sensor measurements. The combination of an affordance-based suitability network with an ad-hoc approach in an indoor environment has not been published before and extends previous papers [3,12–14].

The research question of this paper deals with the conceptual modeling of a context-sensitive, ad-hoc suitability network to support indoor manufacturing transportation processes. In detail, the paper strives to analyze if an affordance-based, ad-hoc approach to generate suitability networks for the calculation of "optimal" transportation paths in an indoor manufacturing environment reduces the computational complexity to calculate optimal paths—in comparison to the initial network. In addition, we analyze if the generated ad-hoc network allows re-routing if relevant incidents in the manufacturing environment occur. Generally, the ad-hoc aspect refers to the time of the network generation—i.e., after a manufacturing step has been finished—and the fact that each production assets' transportation requirements as well as quality relevant incidents have to be considered.

The structure of the paper is as follows: Section 2 starts with relevant work leading to the indoor manufacturing space and processes under review as well as a linked manufacturing data approach as spatial cyberinfrastructure comprising manufacturing data in Section 3. Section 4 defines the methodology for the affordance-based spatial suitability calculation focusing on ontologies, affordances and the suitability determination process and the ad-hoc aspect. Section 5 elaborates on the analysis of the proposed algorithm for the affordance-based ad-hoc suitability network to a classical shortest path algorithm. Section 6 highlights use-cases of the optimal path calculation in a manufacturing environment. Finally, a conclusion and a discussion is given in Section 7.

2. Relevant Work and Research Approach

This section highlights the literature related to this research and the general research approach followed in this paper. In the relevant work we elaborate on the contributions from GISc—in particular modeling indoor space, ontologies, and routing. In addition, Cyber-Physical Systems for manufacturing environments are of relevance for this paper. The description of the approach elaborates on the overall methodology followed in this paper.

2.1. Relevant Work

In order to support decision making in indoor manufacturing environments, there is a requirement to understand the manufacturing processes under review. A basic description of semiconductor manufacturing is given in [8]. Due to the emerging automation in manufacturing—known as smart manufacturing or Industry 4.0—there is a strong need to support decision making in order to enhance the competitiveness [15]. In the literature, there are several approaches to increase the efficiency of manufacturing lines [6,15,16]. To utilize optimization results [17] describe wearable devices for managers and employees of manufacturing companies. The authors of [4] propose that manufacturing decision making can be supported by adding the dimensions space and time to production related data.

Modeling indoor space and Geographic Information Systems for indoor purposes are active research fields, as there are a number of recent publications in this field. Modeling indoor space is of interest for GISc as a person resides approximately 90% of their daily time inside a building [1,2]. Modeling indoor space was first demonstrated by [18,19] focusing on wayfinding inside airports. In literature there are several approaches to model indoor spaces [20]. Ranging from topological models (e.g., [21]), hybrid models—where: both topology and geometry of the indoor space are part of the model [22–24], hierarchical models (e.g., [25]) and semantic models (e.g., [21,26]. In addition, Building Information models are used to model indoor space [27].

Ontologies, are an approach to formally describe a universe of discourse. A discussion of ontologies in scientific literature is given in [28,29]. An ontology according to [30] denotes the formal explicit specification of a shared conceptualization. There are different types of ontologies such as i.e., a domain ontology, representing a specific domain in an abstract way including the physical world and their behavior [19]. Authors in [31] adds entities, relations and rules as main elements to ontologies. Among others, Refs. [32,33] elaborate on the spatial dimension of ontologies.

In order to support routing and navigation in an indoor environment several approaches exist in literature. A more general approach to model graphs for indoor routing and navigation is presented in [21]. The idea of graphs is based on the concept of duality [20,24]. In addition the OGC standard IndoorGML uses duality concepts for generating indoor routing graphs. The authors of [34] elaborate on an approach to compute indoor paths avoiding obstacles and groups of obstacles. In study [35], the authors propose a methodology to generate accessibility information for impaired people. The authors of [36–38] elaborate on the application of affordances for path calculation and decision making of pedestrian agents. In order to model spatial suitability, the authors of [39] provide a hierarchical representation of indoor spaces considering user groups and their tasks. Furthermore, the authors of [12,13] provide an affordance-based approach to model spatial suitability for routing and navigation. In detail, they implement and evaluate the model on a routing scenario for mobility-impaired persons.

According to study [40], there is the need to integrate positioning data with domain-specific information to ensure data interoperability via linking data. The huge benefit of such linked geo-data is the improved data discovery and reusability of the data. Therefore, the authors of [40] developed a geo-ontology design pattern for semantic trajectories to show the applicability of linked geo-data on interdisciplinary, multi-thematic and multi-perspective data on the use-cases of personal travel and wildlife monitoring.

2.2. Research Approach

The overall approach followed in this paper can be described as follows. Based on an indoor ontology—describing the indoor manufacturing space—and spatial data on the indoor space, we evaluate an affordance-based routing approach for transportation tasks of production artefacts. The determination of a path in the indoor space is based on a network (i.e., a graph). The affordance-based approach, described in this paper, calculates individual suitability values (i.e., edge weights) depending on each production asset, and thus may reduce the complexity of the graph—which in turn reduces the computational complexity of a path calculation—e.g., shortest path. The novelty of this approach is, that this step is done with the help of an ontology.

In detail we develop a methodology to calculate individual spatial suitability values for the indoor space for each production asset at the time a route needs to be calculated. Additionally, this methodology supports the determination of the target of the route, based on the suitability values (i.e., if a certain manufacturing step can be performed on a piece of equipment). The result of this methodology is a network—called ad-hoc navigation network in this context—with calculated weights.

The results are theoretically evaluated with respect to the computational complexity of a shortest path calculation. Finally, the approach is applied to a case study in a semiconductor manufacturing site.

3. Indoor Manufacturing Space and Manufacturing Processes

This section describes the indoor space and the objects in this environment, which is required to understand the necessity for an ad-hoc network generation in this context. The manufacturing context in this paper is a semiconductor production facility, which is special, due to the cleanroom conditions. This section relies on the work evident in studies [8,9,17].

3.1. Indoor Space of the Manufacturing Environment Under Rreview

The indoor space under review is a semiconductor production facility. The manufacturing processes are done in a cleanroom environment. Any cleanroom ensures that the air inside has a low contamination with particles—in size and quantity. Cleanrooms are expensive to construct and maintain. Hence, they are constructed as compact as possible, which induces that the space for manufacturing equipment and movement of people and production assets is limited. In order to enter or leave a cleanroom there are defined entry points that are "secured" with airlocks. To change from one cleanroom into another requires the use of an airlock—in order to avoid the transfer of particles, especially when the cleanrooms are of different air quality classes. The cleanroom floor shows a special design that ensures a vertical laminar flow of clean air. The floor consists of single quadratic elements that reside on a frame structure—which might get bumpy due to the heavy wear or construction work.

In general, the movement of operators and production assets is restricted to the walkable areas of the cleanroom. Assets are transported on a trolley, which is pushed by a human operator or by an autonomous transportation via a transport system. Additionally, operators are allowed to carry production assets. The movement of operators and production assets might be restricted due to quality issues. Some asset types are prone to contamination from chemical processes. Hence, certain production asset types are not allowed to enter specific cleanroom areas—to avoid contamination. As the production facility is located on several floors, the production assets change between floors using elevators or staircases (requires the asset to be carried).

A spatially enabled sensor network is established in the manufacturing environment to ensure the quality of the cleanroom environment. The sensor network comprises of fix installed sensors with known locations measuring environmental parameters (i.e., air quality and contaminations) whereas moving sensors, which are located i.e., on trolleys, to detect bumpy floor areas. Generally, the sensor network supports a complete monitoring of each asset between and during manufacturing processes.

Manufacturing processes are a process chain that consist of a several hundred single steps—defined in a specific production plan. The production steps are not aligned on a conveyor belt, because the factory produces a high number of product types having different process chains. Additionally, each production step can be carried out on different equipment, which are geographically dispersed over the production facility. Thus, the transportation processes show a multifaceted structure due to the multitude of product types, according process chains/plans and manufacturing equipment. The degrees of freedom—due to the number of suitable manufacturing equipment for each manufacturing step and their geographical dispersion—present in the production line, indicate that transportation processes are a complex decision problem.

The production line differs from ordinary indoor spaces and production environments. Offices and/or residential buildings show a division into rooms and corridors. In a semiconductor manufacturing environment, rooms are hardly present, whereas corridors of considerable length are the main organizing structure. The layout of the indoor space under review is unstable, due to changing market demands. This requires equipment to be relocated, removed or the installation of new manufacturing equipment. The mentioned actions may change the layout of the production environment temporary or permanently, which has consequences for the transportation processes of production assets.

3.2. Spatial Cyberinfrastructure for Manufacturing Data

The implemented spatial cyberinfrastructure based on a graph-database and RDF supports manufacturing data with near real-time capabilities—smart manufacturing. Due to the facts described in Section 3.1, the spatial cyberinfrastructure supports a semantic annotation—ontologies—including manufacturing data, tracked positions, historic processing information and future processing information. Therefore, a spatial graph database is implemented as basis for the spatial cyberinfrastructure—including the spatial and temporal dimension. This paves the way towards a just in time analysis and ad-hoc spatial suitability assessment to support navigation based on affordances in a proper manner.

Therefore, Figure 2 shows a visualization of the corresponding data described in Section 3.1 similarly to the Linked (Open) Data Cloud [41]. Figure 1 subsumes ontology classes for semantic annotations, historic and future manufacturing data and spatial information. The example shows an abstract basic top-level of the Linked Manufacturing Data, in which the physical location unions semantic annotations in blue, spatial information in green and manufacturing information in yellow. Therefore, [42] give examples how linked manufacturing data supports historic and future processing data.

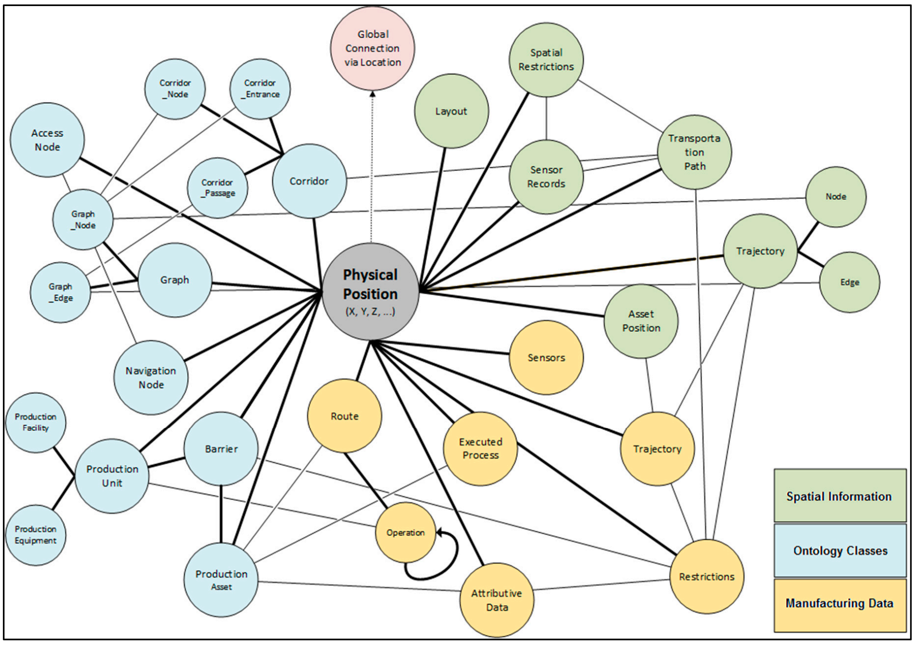


Figure 2. Linked Manufacturing Data for Transportation Tasks according to studies [3,41] at an abstract top level. Thick styled links represent the hierarchical structure of linked data, whereas thin styled links represent data links between different data sources.

4. Methodology for Affordance-Based Spatial Suitability Calculation

In the semiconductor manufacturing environment the production assets are transported from one manufacturing equipment to the next processing step. Each production asset (type) has peculiarities that have to be considered when planning a certain transportation route. The contemporary workflow in the manufacturing environment requires humans to decide on a path. Due to the presence of several hundred different production equipments, an operator can hardly know all relevant asset characteristics.

4.1. Ontologies and Affordances

The approach proposed in this paper is based on the concept of affordances [10,11], and is similar to that presented in [12]. The term affordance, coined by Gibson [10,11], based on the verb "to afford" is defined as follows:

> "The affordances of the environment are what it offers the animal, what it provides or furnishes, whether for good or ill" ([11], p. 127).

Thus, a chair offers the possibility of seating for a human being. The offering "to sit" is a result of its properties, and the capabilities and properties of the acting agent as well [11]. Hence, a chair designed for humans, does not afford sitting for an elephant, due to the size and weight of the animal in relation to the properties of a chair. Hence, with respect to Koffka [43], the term affordance can be expressed by the following sentence: "Each thing says what it is" ([43], p. 7).

In the field of GIScience, Jordan et al. [44] utilized affordances for modeling places in a GIS. They propose to model three aspects in order to describe a place: agent, environment and the task. In [44] the affordances of a restaurant are mentioned as example, where the authors evaluate the suitability of restaurants for customers. Therefore, the capabilities and preferences of the agent (i.e., customer) and the task (e.g., socializing, eating) need to be defined.

In the specific context, the determination of affordances of each indoor entity was done in a semi-automated way. First, the objects were analyzed regarding their connectivity (e.g., different floor levels, connecting different halls) and their navigation "offerings" (e.g., turn right, left). In addition, the offerings in terms of manufacturing capabilities and restrictions were determined by analyzing manufacturing related data.

4.2. Determination of Spatial Suitability

In the context of this paper—production assets residing in an indoor manufacturing environment—several production asset types are present. Each production asset type shows specific properties that have to be respected. In order to decide on a transportation path for a production asset, a destination point and a path connecting destination and current position with its suitability, need to be determined. In this process, finding a destination point equals to finding a manufacturing equipment offering a certain production process.

The methodology relies on characteristics of each production asset that are as follows:

- Product type: The product type provides implicit information on the manipulation of the production assets. Specific types need to be handled with care, as they might break easily. Thus, transportation over stairs or "bumpy" cleanroom sections are restricted. Other types are able to move through contaminated or low quality cleanroom areas due to a specific enclosure. The mentioned enclosure has to be carried with both hands, which means that the operator is not able to open doors. In addition, the product type defines other impediments to transport, such as air quality or contamination risks.
- List of manufacturing operations: This information stores the sequence of manufacturing processes that have to be carried out. As several processes can be performed on several pieces of equipment, the resulting quality of the manufacturing processes may differ. Hence, each production asset should choose a production equipment that fits 'best' in terms of manufacturing quality.

To calculate spatial suitability, we break the processes down into tasks and sub-tasks—which follows the approaches of the authors of [12] as well as [45,46]. The methodology—depicted in Figure 3—decomposes each transportation task for each production asset, starting from the overarching next objective, e.g., "move to the next production step 'ion implantation' starting from cleaning station #5". The algorithm identifies the sub-actions of this intended transportation process, based on the following procedure: The algorithm analyzes available equipment offering "ion implantation" with respect to the production asset at hand. If there is more than one equipment offering the manufacturing step, the algorithm looks at additional properties with respect to the production asset—e.g., defect and/or failure rates—in order to apply a weighting of the equipment. Each target equipment, that affords the manufacturing process, is analyzed in comparison to the source equipment—here the source is the cleaning station #5 and the target is an 'ion implantation' equipment. This results in geographical differences—e.g., different floors, different location in the production hall. In order to determine the sub-actions, the algorithm then "moves" backwards from the target to the source—i.e., tries to reach the source. In this way, the sub-actions can be determined—like 'switch floor, 'change production hall'.

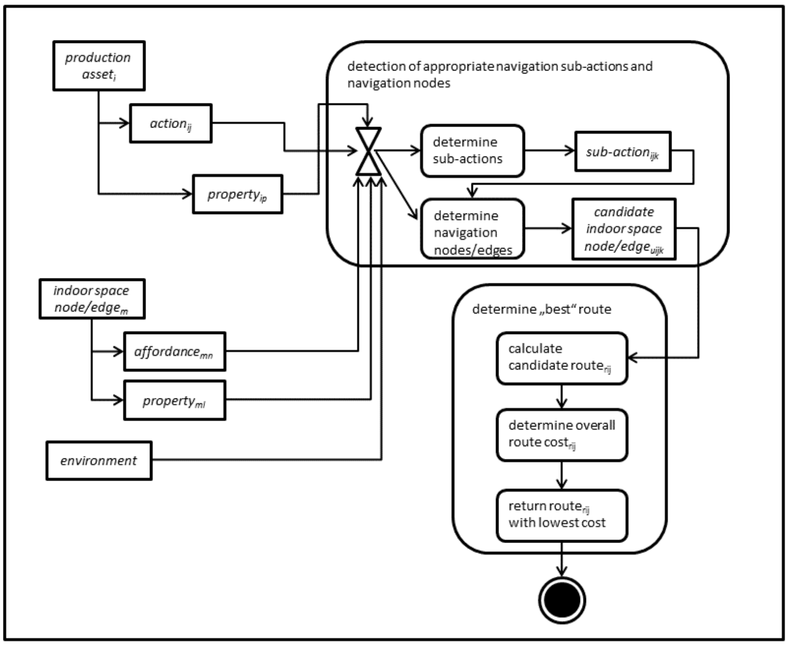


Figure 3. Approach to calculate the suitability of possible routes in an indoor environment, based on affordances (from [3]).

Based on identified sub-actions, the algorithm determines locations and indoor entities that afford the necessary sub-actions. An example for an indoor entity that offers a sub-action called, 'transfer from floor 3 to floor 2', is an elevator. Similar to the approach in [14], we state that the affordances are not strict binary properties. We propose that affordances should be modeled close to the concept of suitability. Hence, in this paper we express an affordance as a rationale number with respect to the environment, the task and the agent. For instance, a staircase and an elevator afford to change the floor level in a semiconductor manufacturing environment. Nevertheless, most operators would prefer the elevator, due to the reduced risk of falling and damaging the assets. The suitability is expressed in the following formulation.

A production asset—denoted as $agent_i$ has several actions to perform—denoted as $action_{ij}$. Actions are specific for each agent, which justifies the indexation i, j. Each agent has a set of properties, where each property is indexed with p. Hence, the properties for each agent are stored in the variable

$property_{ip}$. A traversable network consisting of vertices and edges, where nodes have associated properties and affordances, represent the indoor environment. Each network $node_m$ has multiple affordances stored in variable $affordance_{mn}$, and several properties denoted as $property_{ml}$. Multiple affordances and properties are necessary to describe different actions/tasks possible at each node.

The algorithm determines sub-actions for each asset, which is a gradual refinement of $action_{ij}$. Each action is broken down into sub-actions until each sub-action is decomposed to the basic level. The basic level is reached when each sub-action can be matched with an affordance of a node—i.e., when a node can fulfill the action needed. An example is the movement of a production asset from equipment X to another equipment to perform operation Y. First, the algorithm determines which nodes—i.e., equipment—are offering operation Y. Assuming that the equipment offering operation Y is on another floor, the algorithm identifies sub-actions like 'change floor'. Subsequently, the algorithm determines navigation nodes that fulfill the need 'change floor'—i.e., searches for nodes affording changing the floor.

In addition, the $property_{ip}$ of *production asset*$_i$ needs to be considered in determining the suitability of a specific node or edge. This represents the suitability of a navigation node or edge to be traversed by *asset*$_i$. The suitability of a navigation node or edge for *sub-action*$_{ijk}$ is a function of the affordances and properties of *indoor space node*$_m$ or *indoor space edge*$_m$ and the sub-actions and properties of *asset*$_i$. An example is the suitability of a staircase or a bumpy ground to be traversed by a thin product asset. In both cases, the properties of the indoor nodes in conjunction with the properties of the thin asset, result in a low suitability. This is due to the fact, that this thin production asset can only withstand low vibrations and shocks. As a result we get the list of *indoor space nodes* and *indoor space edges* with their according suitability values for *asset*$_i$.

The suitability values are defined as the quotient between properties and capabilities of *asset*$_i$ and the corresponding offering of the indoor node or edge for ratio scaled properties, like acceleration values, particle concentration per m^3 air, or manufacturing defect rate of the asset type at a specific equipment. For binary values, like accessibility (true/false) we use a binary suitability value. The suitability values present at a specific edge and node are added up in order to get one suitability value per graph element. If one suitability value equals to zero, we regard the edge or node as not traversable.

The resulting lists of *candidate indoor space nodes*$_{uijk}$ and *candidate indoor space edges*$_{uijk}$ serve as basis for the generation of the *candidate routes*$_{rij}$ (for each *action*$_{ij}$). A candidate route is defined as a traversable connection between two indoor navigation nodes—that represent the beginning and end of a task or an action. An example is the movement from equipment X to an equipment offering the next manufacturing process Y. As several equipment may exist that are capable of performing operation Y, and several possible paths connecting equipment X and the equipment offering operation Y, the algorithm may end up in suggesting several different candidate routes. By using a shortest path algorithm—Dijkstra—with (a) length (distance) and (b) suitability values as costs we are able to compute the most suitable route with respect to the action of the specific production asset.

4.3.The Ad-Hoc Aspect

The calculation of an optimal path for each production shall avoid potentially harmful spots in the manufacturing space and shall react dynamically on equipment breakdown or existing bottlenecks. Hence, the calculation of an "optimal" path containing all manufacturing steps—from raw to final product—seems not advisable, as the conditions in the manufacturing environment may change quite rapidly. This is based on e.g., equipment breakdown, relocation, or removal. Additionally, the constant change of market demand and altered production necessities may require a shift in the production capacity. Additionally, incidents—like contamination issues, or malfunctioning airlocks—may happen on a random basis, which need to be considered when generating an optimal path.

In order to overcome the aforementioned issues, we propose generate the spatial suitability graph and the path calculation in an ad-hoc manner. This ad-hoc aspect is realized by a calculation of the individual suitability network immediately after a production asset finishes a manufacturing step. At this stage, a production asset requires to be transported to the equipment capable of performing the next manufacturing step. Exactly at this stage the algorithm is able to consider the "state" of the manufacturing environment in relation to the specific asset—e.g., contamination, bumpy floor. If the indoor space might be harmful for the quality of the specific asset, then the corresponding edge and/or node is not included in the suitability network.

An example for such an incident is a sensor that monitors particle contamination in the indoor cleanroom. Let us consider that the air cleaning system in a particular area is malfunctioning, resulting in a high concentration of particles in the cleanroom. In the manufacturing site under review the wafers are stored in different types of boxes. Box Type 1 can be opened any time by humans, whereas box type 2 keeps wafers in a secured and controlled environment, sealed off from the environment, and cannot be opened by humans—only by specific manufacturing equipment. Hence, boxes of type 2 are not endangered when being transported through an area with a malfunctioning air cleaning—whereas boxes of type 1 can be contaminated with particles and damaged.

According to the Merriam-Webster dictionary the term ad-hoc is defined as being for a "particular end or case at hand without consideration of wider application". As the suitability network generated for each production asset, at each time it completes a manufacturing step meets the aforementioned definition—of being calculated for one specific case without wider application—we regard the suitability network having an ad-hoc character. This can be further justified, as the suitability network might look different for each individual asset, and looks different for similar assets depending on their specific position in the manufacturing environment and or degree of completion.

In order to address such ad-hoc aspects we utilize a spatially enabled sensor network distributed over the indoor space. The sensors detect possible contamination risks, as they measure air quality (particles density) and gas concentration throughout the manufacturing facility including their own position. In addition, accelerometers mounted on the production equipment and transportation carts detect uneven surfaces. The sensor measurements are stored in the data storage in near-real time and thus can be utilized when calculating the suitability values.

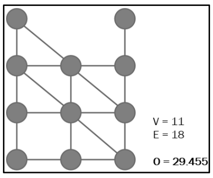
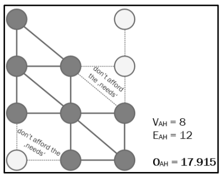
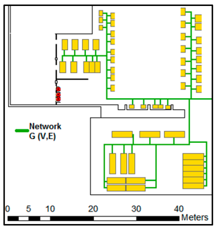
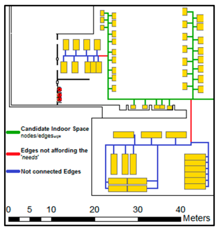
Hence, the approach is able to rely on the current state of the cleanroom environment—which is reflected in the suitability values. This ensures that the algorithm reacts to immediate disturbances, problems in the manufacturing facility, by an ad-hoc generation of the navigation network each time the calculation is done. At each calculation the approach establishes the traversable graph—consisting of nodes and edges), and determines the suitability values of each node/edge.

5. Analysis of the Affordance-Based Spatial Suitability Network for Shortest Path Calculation

The developed approach of the ad-hoc suitability network described in Section 4 is compared with the Dijkstra shortest path algorithm. Therefore, we compare the size of the graph—edges and nodes/vertices—and the computational complexity of the algorithm. Then, we evaluate the computational complexity based on an example, comparing the complete graph or the graph induced by the affordance based methodology. Next, a single 'personalized' transportation process for one production asset in a small area of a production hall is highlighted. This small area is then used for the assumption of the computational complexity of one complete production hall. Due to confidentiality reasons, we are not allowed to use accurate values for distances. Additionally, we have to disguise the manufacturing layout due to confidentiality.

In Table 1 we compare the size of the graph. First, we analyze the complete graph, which is a basis for the Dijkstra shortest path algorithm—denoted as $G(V, E)$. For the ad-hoc network we use $G_{AH}\ (V_{AH}, E_{AH})$. The ad-hoc network graph is a subset of the complete graph $G_{AH} \subset G$, because edges and nodes that do not afford the 'needs' are excluded. Hence, the computational complexity of the Dijkstra algorithm $O = (|V| * log(|V|) + |E|)$, is higher than the computational complexity of the ad-hoc network $O_{AH} = (|V_{AH}| * log(|V_{AH}|) + |E_{AH}|)$, if the same graph is the overall basis of the computation.

Table 1. Comparison of a classical Dijkstra shortest path algorithm and the Ad-Hoc Suitability Network Algorithm to identify optimal indoor transportation.

	Classical Dijkstra	Ad-Hoc Network Using Dijkstra	Comparison
Basis: G—Graph V—Vertices E—Edges	**G** (V, E)	$\mathbf{G_{AH}}$ (V_{AH}, E_{AH})	$\mathbf{G_{AH} < G}$
Complexity: (optimal)	**O** = (|V| × log(|V|) + |E|)	$\mathbf{O_{AH}}$ = (|V_{AH}| × log(|V_{AH}|) + |E_{AH}|)	$\mathbf{O_{AH} < O}$
Abstract Example:			$\mathbf{O_{AH} < O}$ **17.915 < 29.455**
Single Transportation Process in ~$^1/_4$ of one production hall: (Affordances of Vertices and Nodes considered for the "*candidate indoor space nodes/edges*$_{uijk}$")	For each transportation process of a production asset, the complete graph-based network is considered for the shortest path calculation. Spatial Suitability is calculated for the complete graph.  V = 123 E = 123 **O = 380.058**	At the beginning, the candidate indoor space nodes/edges$_{uijk}$ is calculated based on the 'personalized' ad-hoc network. Therefore, first the edges have to afford the 'needs'. Second, for each calculation equipments have to affor the 'needs' for the operation. Spatial suitability is calculated for the candidate indoor space nodes/edges$_{uijk}$.  V_{AH} = 68 E_{AH} = 68 $\mathbf{O_{AH}}$ **= 137.832**	*"One transportation path calculation, each asset has a few hundred of them."* $\mathbf{O_{AH} < O}$ **137.832 < 380.058**
Calculation considering one production hall: (Assumption based on the previous example)	V = (123 × 4) = 492 E = (123 × 4) = 492 **O = 1816.446**	V_{AH} = (68 × 4) = 272 E_{AH} = (68 × 4) = 272 $\mathbf{O_{AH}}$ **= 934.202**	

Note: Exact values are prohibited and white spaces are involved to disguise the layout of the production environment.

A practical example focuses on the transportation process of a single production asset in a small area of a production hall. The approach using only a shortest path algorithm considers the complete existing graph, which is marked with a green line. The ad-hoc suitability network defines the candidate indoor space nodes/edges$_{uijk}$—already excluding edges and nodes that do not afford the '*needs*' of the specific production asset—before calculating the shortest path. This reduced graph is used for determining possible routes$_{rij}$ subsequently. These routes$_{rij}$ are then used for the spatial suitability assessment. Here, the number of possible routes is less than for the complete graph.

6. Case Study: Optimal Path Calculation in a Manufacturing Environment

This section describes a case study of the implemented affordance based calculation of optimal paths in the manufacturing environment based on an ad-hoc suitability network. Thus, a proof of concept of the implementation is provided in Section 6.1 of the determination of the ad-hoc suitability network. Section 6.2 addresses the decision of the optimal route based on defined affordances and shows how the optimal can equal the shortest path and how it can differ.

6.1. Implementation of the Ad-Hoc Suitability Network for a Smart Transportation Process in a Flexible Manufacturing Environment

The implementation of the workflow presented in Section 4.2 results in a developed Java Application. This application utilizes a previously developed spatial graph database, presented as linked manufacturing data approach [42]. The linked manufacturing data approach serves as basis for the research as it provides the digital representation of the indoor manufacturing environment at hand, the corresponding manufacturing data and semantic annotations of manufacturing data and the environment. Therefore, the spatial graph database is queried from the implemented Java Application via implemented procedures in Cypher and comparison of semantics and manufacturing data is done in the computed application.

Intermediate results of the implemented approach can be seen in Figure 4. In Figure 4, the first intermediate result is depicted as the basis network for the overall route calculation, layout and equipment as well as the starting point for the transportation process. The next two intermediate results in the middle of Figure 4, focus on the affordances of the nodes or edges derived by the linked manufacturing data approach and the semantics. A comparison is made separately if the edges/nodes afford the needs of '*to transport*'. On top, edges are matched with their affordances and if they are suitable for the production assets' needs or not. Green edges afford the needs and the red edges do not afford the needs. Blue edges afford the needs, but are not connected anymore. The compared nodes for simple action such as turn left or right afford the needs, except nodes representing an equipment. These are matched with the next operation and if the equipment support the needs for this operation. Such suitable equipment is visualized in green. The combination of both intermediate results presents the *candidate indoor space node/edge*$_{uijk}$ as intermediate result and as basis for the further suitability assessment for each possible route. Figure 4 shows as a result the 'personalized' ad-hoc network for a production assets' transportation task, as combination of affording nodes and edges. The result shows that only suitable equipment is connected to the network if there is a possible connection via edges. A topology check removes edges with only one node (blue lines).

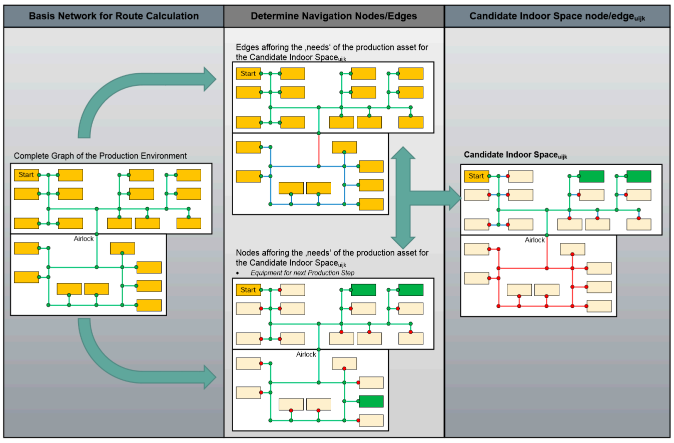


Figure 4. Intermediate results of the implemented approach from the complete graph as starting point to the candidate indoor space node/edge$_{\text{uijk}}$ including affordances.

The *candidate indoor space node/edge*$_{uijk}$ is then refined by the developed application, as edges and nodes which are not part of a possible route to suitable equipment are removed. Therefore, built-in shortest path queries are used from neo4j spatial queried by the application. For this calculation, a default length of zero is assumed to return all possible paths from the starting point to each suitable equipment. Figure 5 shows further results of this calculation of candidate routes, with the basis of the candidate indoor *space*$_{uijk}$ with affording edges and nodes (in green) on the left side. In the middle, Figure 5 depicts the next limitation of the ad-hoc network comprising only the candidate *routes*$_{rij}$. On the right side each route is displayed separately.

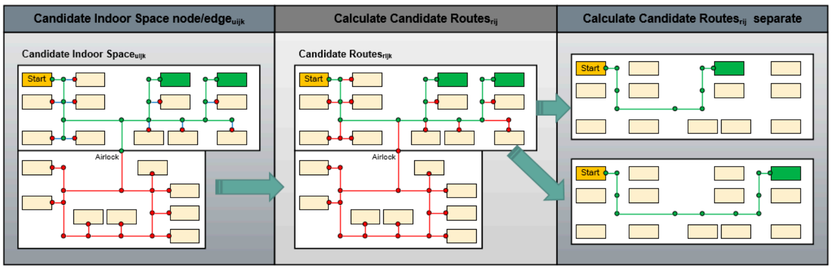


Figure 5. Intermediate results showing the limitation of the *candidate indoor space node/edge*$_{uijk}$ to all possible *candidate routes*$_{rij}$.

This *candidate routes*$_{rij}$ are the basis for the suitability assessment, and thus the final result of the ad-hoc suitability network. Therefore, the sensor network is mapped to the prospective candidate routes via either a spatial join of the sensors and nearby edges or via a fixed definition of the sensor and possible affected areas/edges. This suitability assessment of the sensor measurements can be triggered via events, whereas only the candidate routes have to be adjusted and re-calculated for the final route decision or a detour. The sensor measurements are weighted according to the production assets' affordances and mapped onto the corresponding edge, which is then used to identify the route with the least cost as the optimal path.

In comparison to existing approaches, the presented methodology outlines the optimal path computation based on an ontology. The proof of concept utilizes affordances of the indoor production environment and the production asset. The optimal path computation considers what the indoor environment offers to the production asset and identifies the individual transport suitability alongside with disturbances occurring in the indoor space. Hence, our approach has the advantage of reducing the computational complexity of path calculations, due to a reduced navigation network. In comparison, authors of [47] focused on a semantic navigation approach focusing on human navigation. They developed an approach to calculate the best traversable path between a start and an end point, with respect to the user's capabilities. Nevertheless, the paper does not utilize the concept of affordances explicitly. In addition, the paper does not include an ad-hoc component, as users are redirected to the original planned path, in case they get lost—neglecting the possibility of generating a new path. In the studies [48,49] the authors present empirical studies identifying the least risk path for human indoor navigation. In the papers a path between two points are calculated that has the least risk of getting lost. Thus, the papers highlight an approach for calculating a least-risk path without including different user's preferences. The research in this paper focuses on generating optimal paths for production assets, which might have a certain risk of getting lost. However, the production asset is the focal point for the path computation and not the human, as will be equipped with an indoor navigation assistance system.

6.2. Use-Case: Optimal Route Decision Based on Affordances and the Ad-Hoc Suitability Network

The identification process of the optimal route is based on the suitability assessment of the *candidate routes*$_{rij}$, therefore the overall the workflow determines the overall *route cost*$_{rij}$. For this suitability assessment, the sensor measurement values are compared with affordance. The developed application classifies the measurement value, the worse the measurement value, the higher is the impact factor of the sensor on nearby affected edges which is multiplied with the length of the edges. Finally, the application returns the $route_{rij}$ with the lowest cost representing the optimal path in terms of length and quality. This is applied on two case studies based on the before created ad-hoc suitability network and the corresponding $candidate\ routes_{rij}$.

The first case study is depicted in Figure 6 with the suitability assessment of the two routes named *Route_X1* and *Route_Y1*. One sensor (highlighted with a bigger size) triggers an event as a threshold is exceeded, which is considered for the identification process of the optimal path. As it can be seen in Figure 6, this alerting sensor is affecting *Route_X1* and *Route_Y1*. Therefore, for each route the determination of the overall route cost is done by summing up the respective edge lengths. Thus, in Figure 6 the length for each edge is stated and the thickness of the edge shows, if the edge is affected or not. The impact factor of the measured value representing the suitability is defined as two for sensor1. The calculation of the shortest path is with 30.2 m for *Route_X1* and 39.2 m for *Route_Y1*. By calculating the optimal path and thus by incorporating the suitability assessment based on affordances, *Route_X1* results in a value of 39.4 and *Route_Y1* in a value of 49.1 as the affected edge is multiplied with the impact factor. This case study shows, that both routes are affected similarly by the sensor measurement and the optimal path equals the shortest path.

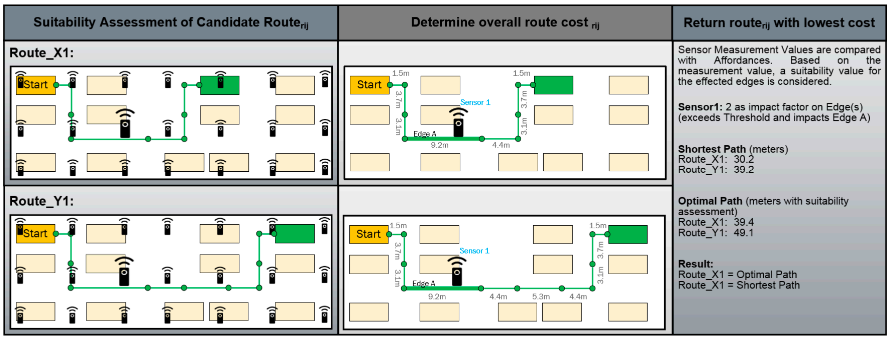


Figure 6. Use-Case: Route determination based on the ad-hoc suitability network where the optimal path equals the shortest path.

The second use-case focuses on the difference between the optimal path and the shortest path. Therefore, Figure 7 has the same basis as Figure 6 with two routes named *Route_X2* and *Route_Y2*, whereas two different sensors *Sensor2* and *Sensor3* exceed the defined thresholds. Based on the spatial distribution of the sensors, *Sensor2* affects *Route_X2* and *Route_Y2* contrary to *Sensor3* affecting only *Route_X2*. The impact factor of *Sensor2* is determined as 2 and the impact factor of *Sensor3* as 3, as a worse value was measured. The calculation of the classical shortest path equals the calculation of the first use-case. The difference is in the calculation of the optimal path combining suitability and length. Route_X2 has more edges which are affected by the sensors than Route_Y2, also with a stronger impact factor. Therefore, the calculation of the optimal path shows that Route_X2 has a value of 45.1 and Route_Y2 a value of 44.3. This means, that Route_Y2 is the optimal path and that the optimal path does not equal the classical shortest path depicted in Figure 6.

The case studies show that a longer path is accepted if it is necessary to maintain the quality of the production asset, or if the subsequent manufacturing step is not reachable on the shortest path—e.g., due to the inherent risk for the production asset. Hence, it seems advisable to make a detour to avoid e.g., areas with a bumpy floor with a thin wafer, as they might break easily. A damaged or contaminated production asset—i.e., a silicon wafer—has to be discarded. Depending on the degree of completion of the asset the company loses the invested manufacturing capacity and time (several hours to several days/weeks). Thus, any manufacturing company is committed to avoiding quality risks and to reducing scrap.

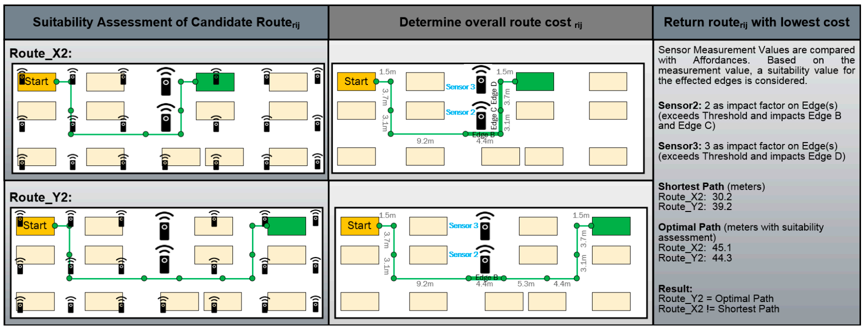


Figure 7. Case study: Route determination based on the ad-hoc suitability network where the optimal path does not equal the shortest path.

7. Conclusions and Discussion

To sum up, the research elaborates on the development of an ad-hoc suitability network for indoor manufacturing based on a previously developed linked manufacturing data approach [42] and an indoor ontology for indoor manufacturing environments [3]. The calculation of an ad-hoc suitability network utilizes the context of production entities, affordances of manufacturing environments, and a sensor network to calculate the spatial suitability (for each individual asset). Based on the spatial suitability the approach calculates the optimal path to transport assets along a graph-based network. The path starts at the last processing equipment and the possibility of multiple target equipment if they afford the *'needs'* of the asset. The ad-hoc suitability network is the basis for identifying the optimal path. In the best case, the optimal equals the shortest path if no sensor measurements exceed a defined threshold. Otherwise, the optimal path can be a detour to avoid potential contamination or other detected incidents. A proof of concept is implemented showing the variability of the ad-hoc suitability network if sensor measurements change. This smart transportation approach uses a spatial graph-database to store the linked manufacturing data, which can be considered as cyber-physical system.

The ad-hoc strategy of the approach is found in two different aspects. First, the suitability network is generated in an ad-hoc manner—exactly when a production asset finishes a manufacturing step and an optimal transport path to the next production step is required. Hence, we calculate a suitability network and an optimal path for each individual production asset. Secondly, the generation of the suitability network considers current disturbances and incidents in the indoor environment, such as contamination issues, air quality problems. Hence, the approach is intended to avoid such areas which are harmful for the quality of the production assets. In this paper, we utilize a sensor network that observes the manufacturing space for any disturbances.

We highlighted the benefit of semantic annotated manufacturing data for the creation of an affordance-based ad-hoc network including only those edges and nodes that afford the 'needs' of the respective production asset. An additional benefit is the use of semantics for the spatial suitability assessment, to link the sensor network with transportation processes and the solving of interoperability issues in the production environment. The novelty of this approach is given due to the fact, that the graph simplification process is purely based on the suitability calculation—which itself is based on an ontology. Thus, we see the combination of an ontology, reasoner, and (shortest) path calculation as a novel idea. The approach is justified by the fact that the manufacturing space under review is highly flexible with several hundred production assets in the facility at the same time, having different degrees of completion. It would be quite difficult to model the interdependencies between indoor space, production assets (at different completion degrees) in a standard database or mathematical model. In our opinion only ontologies/semantics can handle this complexity at hand.

The approach helps to generate a thin navigation network, which reduces the computational complexity of shortest path calculations. Thus, shortest path calculations, necessary for each individual production asset when completing a manufacturing step, require less computing power compared to using the full navigation network.

In terms of the research question, a context-sensitive approach is developed that calculated an ad-hoc suitability network to support indoor manufacturing transportation processes. The results show that our ad-hoc suitability network generates thinner navigation networks, which in turn reduces the computational complexity of shortest path algorithms. As the calculation of transportation paths is a very frequent task, this approach reduces computational power necessary.

The ad-hoc aspect is shown in the case study, where a sensor network monitors the manufacturing environment. If an incident results in a sensor measurement that exceeds the production asset's individual threshold, then the edge or node is not included in the suitability network. Hence, the asset avoids harmful areas.

Future research includes the application of the approach in autonomous transportation solutions in manufacturing environments. Here transport robots are able to load and unload production assets and to move them to the next production step in an autonomous manner. Such a solution needs to consider the spatial suitability for the production asset and the transport robot itself in order to succeed. Before the autonomous transportation solution is implemented, humans pushing trolleys to transport production assets to the next manufacturing step could be supported with an application following a location-based service approach. Therefore, operators transporting assets are supported in their route decision (i.e., they get a recommendation), and are alerted when they should load/unload a specific asset. Such a solution requires some kind of optimization in order to find the "optimal" route for a number of assets. Hence, coupling the ontology—and affordances—with a mathematical optimization approach seems to be a promising approach to solve this issue.

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Chapter 12

Summary

This chapter summarizes essential findings and results of this research in a conclusion. Additionally, a discussion is provided and ideas for future research directions and improvements for the research are presented.

12.1 Conclusion

This research represents a novel approach of bringing Geographic Information Science and Technology (GIS&T) from outdoor to indoor and the application of GIS&T to support an indoor production environment. Smart Manufacturing and Industry 4.0 is supported by covering interesting topics for optimization and quality assurance in respect to affordance-based navigation and spatio-temporal analysis. The main results are an indoor navigation ontology as indoor spatial model, an innovative way to structure and connect data as Linked Manufacturing Data (LMD) approach and the analysis of parallels of an outdoor and indoor task to support the re-usability of GIS&T. The results include a demonstrator including the optimal indoor wayfinding implemented as an affordance-based navigation approach linking the context, spatial suitability and affordances. Methods for spatio-temporal data analyis are shown focusing on Self-Organizing Maps (SOMs) and defined use-cases, to show the potential of this type of analysis.

Indoor Navigation Ontology
The first major result is a developed application ontology 'Indoor Navigation Ontology', comprising the indoor environment, indoor navigation and affordances. This type of an abstract indoor spatial model is used to get a general overview of the environment and the corresponding task. Fur-

ther, the indoor navigation ontology enhances a former re-usability of the application. The ontology is filled with corresponding manufacturing data, to check the logical consistency of the developed data model. Additionally, via a successfully executed reasoning, new data links are implied and added to the indoor navigation ontology. These relationships and further manually added relationships are used to define and model restrictions and affordances for the proposed navigation task based on affordances. The result of the indoor navigation ontology showed occurring problems with the interoperability of heterogeneous data sources and systems into the defined indoor spatial model. Therefore, a novel LMD approach is applied to overcome interoperability problems.

Linked Manufacturing Data Approach

The second main finding is the implemented LMD approach based on the indoor navigation ontology. Therefore, the indoor navigation ontology is integrated into a spatial graph-database following the Linked Data (LD) principles. The LD principles highlight a new and innovative way to structure, publish, discover, access and integrate data (Kuhn et al., 2014). This LD is coined as LMD approach and is the basis for the ongoing research. The LMD approach is used to solve the interoperability problems of heterogeneous data sources and systems. This approach stores data in the Resource Description Framework (RDF) data format as data triples, annotated in the form of subject, predicate and object. By implementing the spatial graph-database, semantic annotations are established, which enable the similarity analysis of manufacturing data and '*walking through the graph*' queries.

Navigation Based on Affordances

Third, smart transportation of production assets in the production environment is implemented as navigation based on affordances. Therefore, the LMD approach is the basis for the further calculation. Navigation based on affordances investigates the optimal path for transportation of production assets in terms of quality. The transportation task is divided into small sub-tasks and each task is solved separately according to the affordances, which means what the environment offers to the production asset. After solving each task, the weighted result defines the optimal path. In example, a stair and an elevator afford both the traversable of an asset, whereas the elevator is much more suitable in terms of quality. Based on this, an ad-hoc suitability network is generated, which includes all possible paths from the starting point to each possible processing equipment. The ad-hoc suitability network is then weighted according to the affordances which is linked with further affordances of the environment and the processing equipment. The result is the optimal path in terms of production quality, equipment quality, spatial suitability and further context.

Spatio-Temporal Data Analysis

Fourth, spatio-temporal data is analysed in two different ways, the analysis based on a heterogeneous data source and the analysis based on the LMD approach. The analysis on a heterogeneous data source focuses on the implementation of SOMs, to analyse the movement behaviour of production assets through the production line. Therefore, used equipments are aligned in the attributive space leading to an occurred quality issue. The SOMs are used in an approach connecting the physical space as the indoor environment, the temporal space and the attributive space. Moreover, the result of the SOMs show the likelihood of assets resulting in a quality issue or the similarities of assets based on used equipment over space and time. The spatio-temporal data analysis based on the LMD approach utilizes spatio-temporal data paired with modelled data semantics. Through this, it is possible to identify potential bottlenecks by analysing the movement of similar production assets based on data semantics. So either potential bottlenecks of the overall Work in process (WIP) in the production line or specific bottlenecks of the WIP of similar production assets can be analysed. The application of spatio-temporal data analysis on the LMD approach shows the potential of similarity analysis paired with space and time.

Mapping Parallels between an Outdoor and an Indoor Task

Last, the mapping of parallels between a smart transportation task carried out in an indoor production environment and in an urban outdoor environment, is executed. Therefore, the complex overall task is divided into small/atomic sub-tasks which are then solved based on affordances. These atomic tasks are solved separately and finally, they are concatenated and weighted according to the respective affordances. This results in a final decision for the optimal solution of the overall task. The mapping of parallels presents an abstract model of a tasks which exists indoor and outdoor. The sub-tasks differ indoor and outdoor, but each sub-task can be solved individually via task-decomposition and affordances. it also has to be mentioned, that the same task can also differ in different indoor environments. Therefore, if the same indoor task is applied outdoor or vice-versa, new affordances have to be defined for the application of the smart transportation task and the weighting of the overall has to be reviewed and adapted with expert knowledge.

To sum up, a novel approach of applying GIS&T in an indoor production environment is implemented. This includes the indoor spatial modelling as an indoor navigation ontology, resulting in a spatial graph-database presented as LMD approach enriching manufacturing data with semantics. The LMD approach is the basis for an implemented smart transportation task as navigation based on affordances combining the context, the environment and spatial suitability. Further, the LMD approach is the data basis for the executed spatio-temporal data analysis focusing on spatio-temporal data analysis and spatio-temporal data analysis paired with semantics. Last, the developed smart transportation task is the basis for the analysis of parallels of a smart transportation task outdoor and indoor, to ensure re-usability of GIS&T outdoor and indoor. The application of GIS&T in an indoor production environment is shown based on a proof of concept. Additionally, the exact potential of GIS&T is not outlined in detail. A detailed evaluation of current business processes and the working behaviour has to be analysed to answer questions such as 'How much time is saved with a smart transportation' as only the applicability is represented and no hardware for the trolley was implemented.

12.2 Discussion

This section discusses the results of the carried out research. First, the developed spatial indoor model including the context, the environment and the affordances is reviewed. Second, the spatial graph database based on the indoor spatial model is discussed, which represents the implemented Linked Manufacturing Data (LMD) approach. Third, thoughts about optimal indoor way-finding for smart transportation processes are made. This is important, as the transportation is essentially for productivity, efficiency and the production assets quality. Fourth, the discussion addresses spatial-temporal analysis of manufacturing data, therefore also similarities are included based on the LMD approach. Finally, thoughts about the mapping of parallels between an outdoor urban environment and the indoor manufacturing environment are made. This mapping mainly refers to the analysis of parallels at a task level - smart transportation task - including task-decomposition and re-usability of the developed algorithm.

Indoor Spatial Model
The developed spatial indoor model is the basis of this research. Therefore, a critical literature review leads to the formal data description based on ontologies. Different types of ontologies exist such as an upper-ontology, a task ontology, a domain ontology and an application ontology. After checking the ontology types and the proofed requirements for the production environment and the research area, the application ontology is chosen. The application ontology fits to the research, as it combines the context as the environment

and affordances and a possible task, which is the transportation task having optimization potential.
A validation of the indoor spatial model is executed, which proofs the logical consistency of the model and reasoning for the establishment of follow up relations resulting in data semantics. Finally, the developed application ontology includes the indoor manufacturing environment, the navigation task for indoor way-finding, the context and affordances as a basis for the further research. It is also filled with corresponding manufacturing data. However, the current solution lacks a real-time approach to keep track of new affordances which have to be generated dynamically also for individual experiments for new types of products.

Spatial Graph-Database
The indoor spatial model serves as a basis and highlights problems with data interoperability, as manufacturing data is stored in heterogeneous data sources. Thus, there is the necessity to link heterogeneous data sources and systems to fit the manufacturing data to the developed application ontology. Therefore, research addressed the Linked Data (LD) paradigm shift of Geographic Information Science and Technology (GIS&T), that offers new ways of structuring, publishing, discovering, accessing and integrating data (Kuhn et al., 2014). To overcome these interoperability issues semantically annotated data, based on the developed application ontology are stored in a graph-database, comprising also spatial information. This has the advantage of the data representation as triples (subject, predicate, object) in the Resource Description Framework (RDF) format. With this approach, the authors apply LD as a collection of design principles and technologies on the indoor spatial model and manufacturing data, leading to a single data source for the ongoing research based on the semantic web. The application of the integrated data and the typed links/relationships show new capabilities of data analysis such as '*navigating*' through the graph to find similarities. The applicability of semantics in a manufacturing environment is shown on certain validated assets, whereas the validation for all production asset types and asset states has to be discussed individually with different divisions including the interpretation of data.

Optimal Indoor Way-Finding to support Transportation Processes
The developed LMD approach implemented as spatial graph-database is utilized for the identification of the optimal path for transportation processes. Therefore, the research discusses trip planning as it is important to calculate the best path in terms of the contextual necessities of a production asset i.e.: the product quality. In case of this research, it is crucial as the decision is directly linked with manufacturing efficiency, productivity and production

quality.
To show a proof of concept of the identification of an optimal path and how this optimal path can vary, a demonstrator is implemented showing the applicability of an optimal path calculation based on a set of defined affordances. The carried out proof of concept shows how environmental influences change the suitability of a path. Therefore, the suitability of a path includes the defined affordances and spatial suitability offered by the environment. The proof of concept is done for a defined set of production asset types and respective affordances. Not yet included is also a dynamic graph creation for the indoor environment, as the walkable ways for human operators between equipment do not change frequently instead of storage locations excluded from the proof of concept. In fact, a multi-modal network is also not considered which could be useful as there is the combination of human transportation and an automated transportation over a conveyor belt.

Analysis of Historical Data based on Space and Time
Manufacturers generate a huge amount of spatial, temporal and spatio-temporal data, which indicates the potential for a spatio-temporal data analysis. The carried out research in respect to the spatio-temporal data analysis is two-folded. It covers on one hand a separate heterogeneous data source and on the other hand the analysis based on the LMD approach. This show respectively either the general applicability of this type of analysis or the ability of matching spatio-temporal data analysis and similarity analysis of semantics. The first part analyses a heterogeneous data source via Self-Organizing Maps (SOMs). SOMs are capable of analysing a high-dimensional attributive space which leads to the extraction of new knowledge. The second part coins spatio-temporal data analysis including similarities of the LMD approach based on a use-case driven approach. The use-cases utilize the similarity analysis of potentially affected assets after an incident and the analysis of potential bottlenecks covering a movement analysis. This demonstration shows the potential of spatio-temporal data analysis of manufacturing data, whereas a validation has to be carried out with expert knowledge for a larger set of production asset types. This is important, as for a final decision making the responsibilities of the analysis have to be clearly stated. In addition, results of the spatio-temporal data analysis can be a further basis for the extraction of affordances for the improvement of the LMD approach.

Analysing Parallels between GIS&T applied Outdoor and Indoor at a task level
GIS&T applied indoor is a novel approach related to current research. Therefore, it has to be proofed if there is the possibility to bring outdoor algorithms to indoor or vice-versa, to re-use applications or methods. The mapping of parallels between outdoor and indoor tasks elaborates on a general smart transportation task comparing the transportation task in a manufacturing environment and the transportation task in an urban environment. Therefore, human task and process planning characteristics are compared and modelled.
The basis for the mapping of parallels is the developed LMD approach and navigation based on affordances for optimal way-finding. The mapping of parallels is carried out by analysing similarities of the task planning, whereas a general task is divided into small/atomic sub-tasks. These atomic subtasks are solved with corresponding affordances, refering to the smart transportation in the manufacturing environment. Via this task decomposition, and solving atomic sub-tasks based on affordances, the way-finding becomes modularized and computational manageable. This modularized approach is validated with the implemented smart transportation approach. For a general statement, further tasks have to be evaluated and analysed which was currently not manageable.

Nevertheless, the applied research shows the potential how GIS&T can support smart manufacturing in a dynamic and flexible production environment. It is proven how data can be structured, combined and enhanced with semantics to support transportation processes and spatio-temporal data analysis including similarity analysis. In addition to the proof of concept, new technologies and databases are used which are still under discussion for the overall applicability for manufacturers. Additionally, it has to be kept in mind that for finalized tools also hardware is essentially such as an intelligent trolley to support a smart transportation.

12.3 Future Perspectives

The current approach shows the application of GIS&T applied indoor with the focus on an indoor production environment. The research shows the preparation of a linked data approach and re-structuring manufacturing data to gain new insights. Thus, indoor wayfinding and spatio-temporal data analysis is executed on identified tasks and use-cases of the indoor production environment at hand. Therefore, this section addresses potential future perspectives of applying GIS&T indoor.

Future Fields of Application

Until now, the carried out research focuses mainly on historical information i.e. for the definition of affordances or spatio-temporal data analysis. Therefore, real-time analysis can be a huge advantage for possible predictive models and the definition of affordances. In addition, spatio-temporal data analysis can be used to identify patterns for some kind of geo-fencing. In a further step, these defined geo-fences could be added to the indoor wayfinding as predicted optimal routes. Therefore, also an alarm has to be triggered to maintain this predicted incidents before they occur. The overall approach as demonstrator is limited to specific use-cases which are validated and tested. For a running application, a wider variety of use-cases have to be considered, evaluated and implemented.

Dynamic Definition of Affordances

In the carried out research, production assets' affordances are derived from a defined conceptualization of the indoor environment and manufacturing data. In fact, a company with ongoing research and development activities has to be flexible by the definition of affordances and thresholds. On one hand, there is the need of self-learning algorithms and patterns which automatically define affordances and thresholds. On the other hand, affordances have to be integrated and adapted within the data model and in the linked data approach. The definition of affordances by hand is also very time consuming and complex. In order to validate the affordances and thresholds , a lot of different expert knowledge is necessary to include exclusions, experiments and ongoing research products.

Indoor wayfinding

Indoor wayfinding is one crucial issue for the carried out research, solved with an ad-hoc suitability network and optimal path calculation. A proof of concept shows the applicability of the proposed concept, adding quality concerns to the route determination. Future interests for indoor wayfinding are focusing on a dynamic creation of the graph-based network to combine possible walking ways and corridors in the production environment. Further, it has to connect equipment and production facilities such as shelves and tables, which are moving frequently. This movement of equipment and production facilities has to be considered within a dynamically updated graph based network. This is an important issue for indoor wayfinding, as keeping track of the graph-based network is very time consuming and hard manual work, with huge potential for improvement.

Mapping of Paralells between Outdoor and Indoor
Future research directions coin the connectivity between outdoor and indoor geography and how to bring outdoor applications to indoor and vice-versa. The research comprises one possibility of the application of a task which can be carried outdoor and indoor. Such a general task is decomposed and refined into atomic tasks which can then be solved, whereas sub-tasks are solved based on affordances. Therefore, again the modelling and definition of affordances is of main interest. Research on parallels between outdoor and indoor GIS&T applications is increasing and emphasizes the re-usability of applications which depends on the field of application or the task.

Finally, the carried out approach shows the possibility of bringing new structures into data via LD principles and the theory of affordances. This is the basis for research topics referring to navigation based on affordances and spatio-temporal data analysis. However, the research addresses the capability of GIS&T applied inside a complex indoor production environment, and there is room for additional indoor geography related research.

List of Figures

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