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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Keywords: Geographic Information Science, Smart Manufacturing, Industry 4.0, Space and Time,

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.

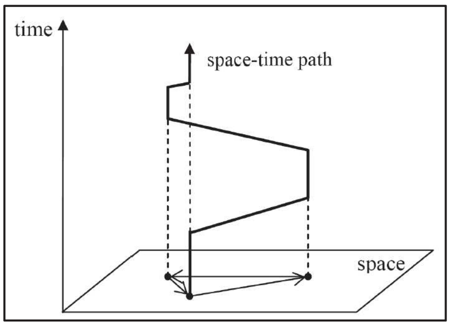

Figure 1: Time and Geography (Graphic from Yu (2006)).

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*".

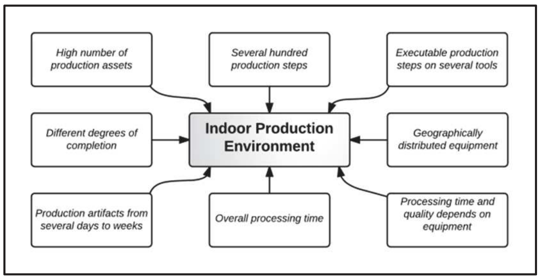

Figure 2: Context-based factors for the indoor production environment in the production assets' point of view.

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.

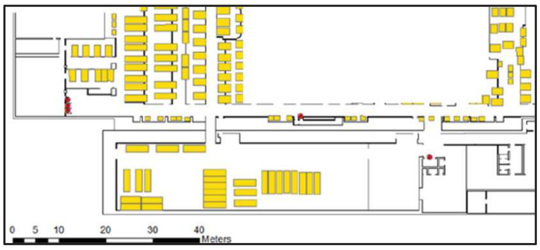

Figure 3: Indoor geography of a production environment using white spaces to hide the exact layout and standardized polygons for visualization purposes.

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.

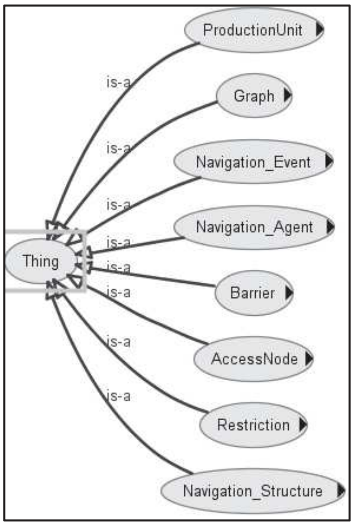

Figure 4: Modified and adapted main elements of the navigation ontology by Scholz and Schabus (2014).

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.

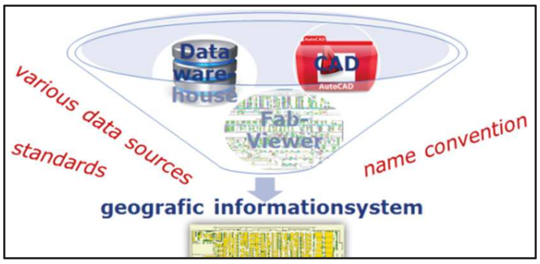

Figure 5: Aggregation of possible existing systems to set up a system building the basis for a GIS.

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.

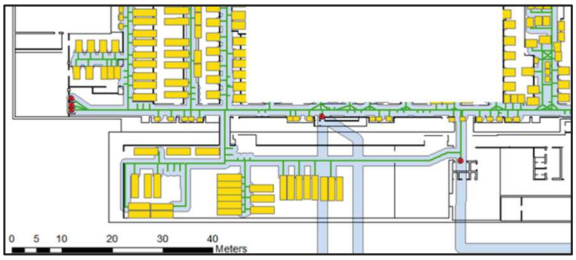

Figure 6: Example showing the graph-based network through the production line environment and possible walking ways as corridors.

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.

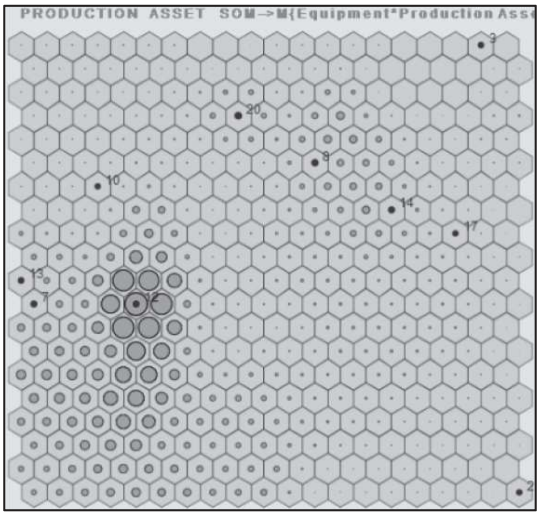

Figure 7: SOM showing a component plane of equipment highlighting the likelihood, if a production asset will be processed or not.

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.

ACKNOWLEDGEMENTS

The work has been performed in the project EPPL, co-funded by grants from Austria, Germany, The Netherlands, Italy, France, Portugal- ENIAC member States and the ENIAC Joint Undertaking.

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