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Research Directions for Merging Geospatial Technologies with Smart Manufacturing Systems

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Reference

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ABSTRACT

As industrial Internet of Things concepts and technologies continue to be retrofitted onto existing manufacturing infrastructure, geospatial considerations, such as asset localization, registration, and tracking, become more critical to ensure better flexibility, capability understanding, and agility. In response, there have been efforts to merge state-of-the-art Geographical Information Systems and Smart Manufacturing Systems in production environments. However, these solutions are often product- or platform-centric and proprietary, such as (i) computer vision technologies embedded on an automatic guided vehicle and (ii) point cloud translation after 3-D scan within a Product Lifecycle Management solution. Standards exist for various steps and functions within these computer-supported pipelines, but little work exists that tests their scalability and robustness. This paper aims to critically evaluate the current state of the integration of Smart Manufacturing Systems and Geographic Information Science and Technology and identifies the potential overlap between the two fields and lists opportunities for further collaboration. The methodological approach of this paper is two-fold: we utilize (a) a survey with experts in both fields and (b) an algorithmic literature meta-analysis. The results reveal that both fields have concepts that could mutually support each other and that smart manufacturing could benefit from Geographic Information technologies—especially from a standardized representation of indoor environments. The results show a great number of potential overlaps and thus present a preliminary roadmap to foster the integration.

Keywords

smart manufacturing, Industry 4.0, standards, geospatial information, systems integration, extended reality

Introduction and Motivation

Often referred to as Industry 4.0, smart manufacturing (SM) refers to the combination of emerging information technology (IT) infrastructure with advanced manufacturing capabilities.[1,2] According to a recent report,[3] industrial wearables, augmented reality (AR), 3-D scanning, and mobile robots are among the top IT trends of the 2020s in manufacturing. To properly integrate such technologies within manufacturing environments, location-based services and Geographic Information Science and Technology (GIS&T) play a critical role.

Over the past two decades, GIS&T research and development have delivered methods and technologies to store, analyze, manipulate, and visualize spatial data. GIS&T research has resulted in, for example, spatial databases, web-based Geographic Information systems, location-based services, and Geographic Artificial Intelligence (GeoAI)[4] as well as modeling indoor space. These technologies and methodologies help in (i) understanding where critical assets are/were at any given time and (ii) linking multilayered data to critical assets within a geospatial context. Recently, there have been several attempts to apply geospatial technology, that is, GIS&T in the broadest sense and geospatial or spatial data in the SM context. Nevertheless, the integration of GIS&T and SM is still regarded as being in its infancy, as smart manufacturing systems (SMS) and GIS&T are hardly coupled using existing standards and available technology to fully realize value form one another.[5]

This paper analyzes the overlap between SM and GIS&T based on an algorithmic literature meta-analysis. In addition, the paper investigates why the combination of SM and GIS&T has not flourished so far based on the results of a survey with experts in both fields. The paper identifies the collaboration approaches and technologies from the fields of SMS and GIS&T for Industry 4.0. Furthermore, the paper elaborates on the following topics:

- prioritization of research directions for GIS&T for SMS,
- identification of standardization gaps that exist between the two perspectives, and
- enumeration of solution areas, emerging technologies, and standards, for example, semantic web technologies, existing SM standards localization, and positioning techniques that might benefit the next steps.

The paper is organized as follows. The section "Background and Related Work" discusses relevant work in the fields of GIS&T and SMS. "Methodology and Experiment Design" presents the underlying methodology for assessing trends, gaps, and opportunities for improving the integration of the two domains. "Results" presents the results of our meta-analysis and expert-driven qualitative assessment. "Discussion on Research and Standards Opportunities" places these results in a deeper context through discussion and the presentation of a preliminary roadmap to integrate SMS and GIS&T more deeply. In the last section, we provide a conclusion followed by an outlook on the research priorities and standard opportunities for the integration of SMS and GIS&T.

Background and Related Work

In this section, we provide commentary on related work that establishes links across GIS&T and SMS for integration. We bucketed these contributions that are (1) GIS&T entrenched, (2) SMS focused, and (3) focused on the integration across the two perspectives.

GIS&T-ENTRENCHED WORK

In the field of GIS&T, modeling indoor spaces has been a research topic of focus. For example, Raubal and Worboys[6] and Raubal[7] elaborated on wayfinding inside an airport. Different approaches to model indoor space have been mentioned by Worboys[8] and Afyouni, Ray, and Claramunt,[9] and in particular, network-based representations have been published by Yang and Worboys,[10] Scholz and Schabus,[11] Knoth et al.,[12] and Nikoohemat et al.[13] Standards in the field of modeling indoor space have been widely developed. The most prominent standards are Open Geospatial Consortium (OGC) City Geography Markup Language (CityGML)[14] and IndoorGML.[15] Both standards have been compared in literature. For example, Ryoo, Kim, and Li[16] and Knoth et al.[12,17] have tried to come up with a standardized (or base) data model for indoor spaces.

Zlatanova, Stoter, and Isikdag[18] elaborated on the use of standards for 3-D information for emergency response. Another strong topic in GIS&T is the integration of Building Information Models (BIMs) with Geographic Information Systems.[19–23] In addition, there is an ongoing initiative to map BIM to Geographic Information Systems (GIS), which is currently standardized through the International Organization of Standardization (ISO).[24] This is of interest due to the fact that the architecture and construction domains utilize BIM to a large degree. To generate spatial data of buildings, several techniques exist in the GIS domain. Indoor light detection and ranging measurements are used that result in point clouds for automated object creation. In the literature, the process to construct semantically enriched objects from raw point clouds is still a challenging topic.[12,25,26]

SMS-ENTRENCHED WORK

Because the treatment of data lies at the core of the SM vision (including its promise of better interoperability[27]), data models and representations are key enablers for wide adoption and dissemination. As a result, the standards development process has been very active in promoting best practices for manufacturers to implement such capabilities. The standards efforts range from semantically handling on-floor messaging, e.g., MTConnect[28] and the Object Linking and Embedding for Process Control (OPC) Foundation's Unified Architecture,[29] design guidelines for additive manufacturing,[30] and data models and guidelines to influence environmental sustainability,[31,32] among many others.[33]

Other standards efforts have addressed the curation of geospatial/location data implicitly. For example, the Core Manufacturing Simulation Data (CMSD) data model,[34] a standard published by the Simulation Interoperability Standards Organization, represents all necessary information to curate and exchange simulation studies between software.[35] CMSD incorporates layout information where assets and workstations reside on the production floor. However, this standard was specifically designed to facilitate import and export functions for commercial simulation software[36] and hence does not explicitly offer solutions for integrating such information into 3-D engines relevant for AR applications.

EFFORTS FOR MERGING GIS&T AND SMS PERSPECTIVES

Other efforts specifically focus on constructing 3-D representations of manufacturing facilities. Such methods vary in the level of precision and detail, ranging from point clouds to fully boundary defined representations.[37] Probably, the most widely adopted approach is to base a 3-D visual representation on a 3-D scan. For example, the adoption of a service-oriented approach for scanning existing facilities is common in the current market, specifically among start-up companies. The outputs of tools based on this approach have been demonstrated to provide high spatial and perceptual accuracy.[38] However, there remains a gap between referencing the virtual (and static) 3-D representation captured with real-world objects.[39] To the best of our knowledge, state-of-the-art solutions still rely on significant human-driven tagging (and tokenizing) of the 3-D representation. That being said, 3-D scanning has proven its value in fulfilling more immersive experiences specifically geared more for virtual reality (VR) applications.[40]

From a different perspective, other groups have focused on constructing data models to provide geospatial representations for indoor spaces. Some of these efforts are accompanied by strong standardization components. For example, the OGC released IndoorGML[41] as a companion to CityGML as standards that aim to provide an interoperable solution to 3-D models of spaces.[42] Hanke, Vernica, and Bernstein[43] discuss development gaps that exist for the use of IndoorGML with other manufacturing standards to contextualize Industry 4.0 data through standards. To suit specific use cases, others have developed their own data models, including an ontology to support indoor navigation in a semiconductor facility[44] and a data model and algorithm for tracking potential safety occlusions in production environments.[45]

Kern and Scholz[46] developed a spatial agent-based simulation for a synthetic cleanroom environment and analyzed the effects of spatial information on the production efficiency. Other papers focused particularly on integrating Geoinformatics into Industry 4.0, where GIS&T and Geo-Semantics have been highlighted.[47,48] More broadly, Rusu et al.[49] leveraged aviation-critical weather data to inform collaborative decision-making with engineering teams. Although Rusu et al. did not specifically address manufacturing-related challenges, they present insight into merging geospatial data into engineering practice.

GAPS AND OPPORTUNITIES

Very few research efforts explicitly call out both Industry 4.0 (or SM) coupled with GIS&T. Because of the dearth of available literature across the two communities, we (along with additional colleagues) held an initial discussion at the Institute of Electrical and Electronics Engineers 2020 International Symposium of Mixed and Augmented Reality (ISMAR)[50] to bring a diverse group of researchers, practitioners, and standards developers together. De Amicis et al.[50] explain that although the research methods (and, more broadly, research thrusts) spanning across SMS and GIS&T are similar, not enough work is currently being conducted on the use of both perspectives in unison. This is particularly true in the standards community. In this paper, we dive deeper into related research, development, and implementation challenges, as detailed in the next section and beyond.

Methodology and Experiment Design

We follow a two-stage methodology consisting of (1) an algorithmic literature meta-analysis and (2) a questionnaire that has been sent out to practitioners in the field of GIS&T and SMS. The literature analysis is intended to uncover overlaps—in terms of terminology—in the scientific literature from 2017 to 2021. The questionnaire is intended to confirm the results of the literature review. The survey was designed in early 2020 and sent out to participants in summer 2020 in order to capture the state of the art concerning GIS&T and SM. The questionnaire was designed with the help of the tool LimeSurvey,[51] which requires only a browser to access the survey. Because of the in-depth questions and free text answers of the survey, the results are regarded as being qualitative rather than quantitative.

Based on the results of the literature meta-analysis and the questionnaire, we are able to combine the findings of both and evaluate the overlap between the two fields of expertise. In practice, the results of the questionnaire are used to back up the meta-analysis and to add some additional aspects that could not be revealed through the literature review.

ALGORITHMIC LITERATURE ANALYSIS GIS&T AND SMS

To understand the interplay between the two research communities, i.e., geospatial information systems and manufacturing, we conducted a meta-analysis of the recent literature in each community. Our goal was to uncover the overlapping keywords between the two communities in an attempt to distill current research trends, gaps, and opportunities.

We leveraged Engineering Village, an academic literature database, to extract metadata for relevant publications, including author-controlled keywords, indexed keywords, abstracts, and titles, among other fields. We restricted our search to the Inspec indexing services. In doing so, we were able to compare indexed keywords directly without performing any term aliasing. We restricted our search to three Inspec-defined indexed terms: "geospatial information systems," "manufacturing industries," and "manufacturing systems." Note that manufacturing-related terms in the Inspec taxonomy do not have as "clean" a root term as GIS&T. As a result, we had to use two search terms to represent the manufacturing space compared with one search term for GIS&T. We restricted our search to papers published from 2017 to present in order to showcase recent evidence of research publications that sit between the two areas of interest. We also restricted the query to records originally published in English.

For each term, we computed a relative contribution to the manufacturing and GIS&T communities. In other words, based on the total records returned in manufacturing and GIS&T, we computed the relative frequency of each term to either community using equation (1).

$$r_i = \frac{r_{mfg,i} - r_{gis,i}}{r_{mfg,i} + r_{gis,i}} \tag{1}$$

where r_i represents the rate of contribution to either field for each, or the ith, indexed term. The range of r_i is normalized between −1 and 1. Here, a score of −1 represents topics that only appear in the GIS&T corpus and a score of +1 represents topics that only appear in the manufacturing (MFG) corpus. $r_{mfg,i}$ and $r_{gis,i}$ represent the total appearances of each term to the MFG and GIS&T queries, respectively. If $r_{mfg,i} = 0$, then $r_i = 1$, and if $r_{gis,i} = 0$, then $r_i = 1$. Based on this metric-per-record, we employ a color-coding method per term that follows all charts and graphs throughout the rest of this article. Based on the absolute frequencies of term appearance along with the previously described metric, we then identified trends and opportunities.

We define "trends" as search terms that have significant coverage in both the manufacturing and GIS&T academic literature (i.e., where r_i is close to 0). In other words, based on our literature corpus, trends represent concepts that are already explored in both communities. As a caveat, this does not necessarily mean that individual papers speak to issues related to geospatial/spatial concepts as well as manufacturing. The trends represent concepts that are already, in some way, understood by either community. It also could mean that there is a substantial level of expertise in the research community. We identified index keywords as "opportunities" if (1) they represent concepts that are only well-established in either the MFG community or the GIS&T community but not explicitly both (i.e., where r_i is close to either −1 or 1) and (2) we consider them to be especially helpful for the community with less coverage based on our expertise. Important caveats for opportunity discovery are that (1) a lack of representation of a specific index term does not demonstrate a lack of work regarding that concept in either research community in an absolute sense and (2) our identification and callouts of specific opportunities are most likely influenced by our own expertise. For the first caveat, we rely on Engineering Village for fully and properly seeding across its indexed term hierarchy. Based on a cursory review of the tens of thousands of search record returns, this is not entirely the case. However, given the scale of our meta-analysis, we can still distill useful insights.

QUESTIONNAIRE

The survey used in this context consists of 23 questions in 6 groups. The questionnaire requires the respondents to select predefined values from lists and radio buttons, whereas other questions prompt responses as free text. The survey, including questions and an overview of results, can be found in the Supplemental Materials.

The objective of the questionnaire is to collect evidence concerning the usage of spatial data, Geographical Information Systems, and standards in the field of Industry 4.0. In addition, we are interested in the hindrances of using standards and future perspectives of GIS&T and SMS. The survey was sent out to approximately 100 practitioners in Industry 4.0 in order to capture the contemporary situation in the industry and the vision concerning spatial data and Geoinformatics. Note that the 100 practitioners were identified by participants of an ISMAR 2020 workshop[50] on merging geospatial technologies in SM. Efforts were taken to ensure the participant pool was fairly balanced between (1) primary fields of expertise, i.e., GIS&T and SMS, and (2) organizational roles (or titles).

Results

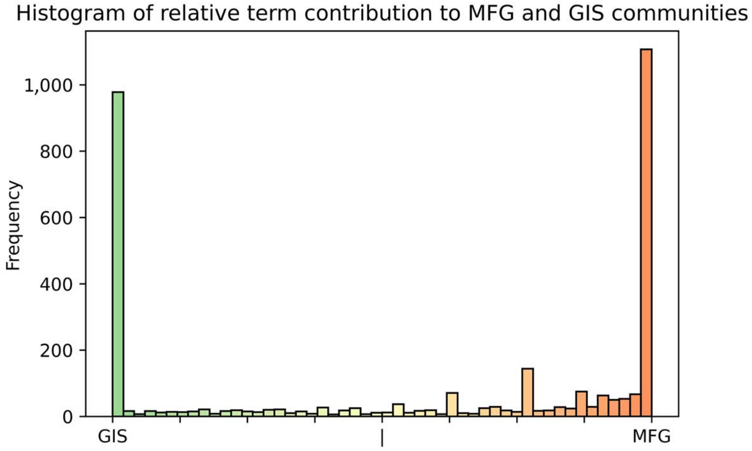
ALGORITHMIC LITERATURE ANALYSIS

The algorithmic literature analysis was performed using the methodology described in the section "Methodology and Experiment Design." The GIS&T query returned 13,623 records and the combined "manufacturing" (MFG) query returned 7,506 elements. We then merged the two queries and removed duplicates by their DOIs. The final data set contained records representing 20,070 publications.

Figure 1 depicts the histogram of the relative contribution of MFG and GIS&T communities. The 3,235 search terms are presented in this chart and are bucketed in 50 bins to create the plot. In this figure, terms fully related to GIS&T are represented by the bar at −1 and terms fully related to MFG are represented by the bar at +1. The color scheme is based on this score of subsequent graphics. In **figure 2**, we depict the terms and their relationship to the respective fields MFG and GIS&T. The terms that are related to the GIS&T field are colored green, the

FIG. 1

Histogram of the relative contribution of terms to GIS&T (at $x = -1$) and MFG (at $x = +1$). Terms that relate to both fields are between the two "poles." The amount of relative contribution to either MFG or GIS&T is displayed on the horizontal axis, with the vertical axis being the total number of terms with that level of contribution.



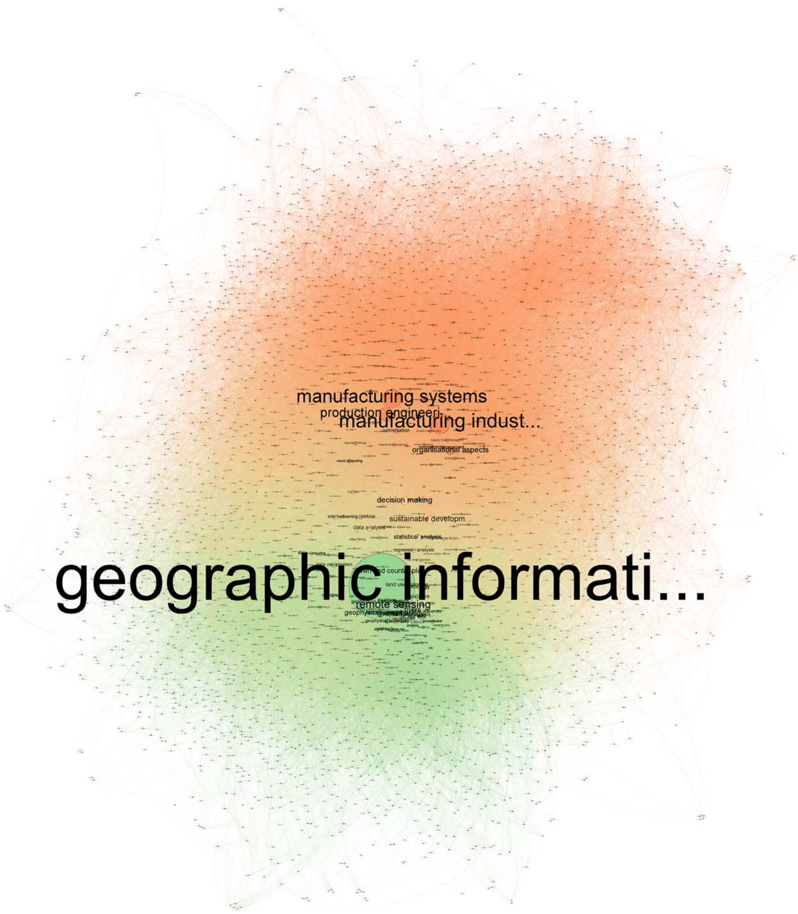
terms that are related to MFG are colored orange, and yellow is used to represent terms that overlap between the two fields. The yellow-colored terms were subsequently analyzed manually to identify trend, gaps, and opportunities. The visual interpretation corresponds with the histogram depicted in **figure 1**, as there are more terms related to MFG than to GIS&T, and the number of overlapping terms seems relatively small. **Figure 2** presents a node-link diagram of the publication data set, representing all 20,070 records. Here, nodes and edges represent index keywords and the co-occurrences of those terms per record, respectively. Node size is proportional to their total frequency across the publication data set. Color abides by the same metric presented in **figure 1**. To construct the network, we deployed a force-directed layout wherein a physics-based model imposes virtual springs on each edge of the network.* Spring strengths are proportional to the number of co-occurrences between two terms. Note that the final positioning of nodes and edges shown in **figure 2** is not absolute. In other words, if the algorithm were to run again, the orientation of the network as a whole could change, e.g., rotation and spread. We let the algorithm run until the node layout was stable and the overall positioning of nodes and edges did not significantly change with respect to each other.

Based on the resulting network, we can distill several insights about the data set. The spread of the orange-colored term cluster, i.e., MFG, is much larger than that of the green-colored term cluster, i.e., GIS&T. This is mostly due to the fact that we had two primary search terms for the MFG cluster, i.e., "manufacturing systems" and "manufacturing industries," whereas for the GIS&T cluster, we were able to capture the research field with one root term, "Geographic Information systems." Furthermore, as shown in **figure 1**, there are a number of terms that almost exclusively belong to either community. As a result, the GIS&T cluster, by definition, more heavily follows the structure of the Inspec taxonomy. In other words, because only one branch of the Inpsec taxonomy is considered for GIS&T, the relatedness of terms is inherently stronger than the MFG cluster. This does not significantly impact the crossover between the GIS&T and MFG clusters, shown as shades of yellow, because the two root terms in MFG are heavily influenced by one another and share lower level indexed terms. This can be seen by the fact that for the two GIS&T clusters, we were able to capture the research field with one root term, "Geographic Information systems." Furthermore, as shown in **figure 1**, there are a number of terms that almost exclusively belong to either community. As a result, the GIS&T cluster, by definition, more heavily follows the structure of the Inspec taxonomy. In other words, because only one branch of the Inpsec taxonomy is considered for GIS&T, the relatedness of terms is inherently stronger than the MFG cluster. This does not significantly impact the crossover between the GIS&T and

*The graph was constructed and laid out using Gephi, an open graph visualization platform.

FIG. 2

Orange represents terms and relationships that solely fit within manufacturing systems and industries. Green represents terms and relationships that solely fit within geospatial information systems. Yellow shows the overlap.



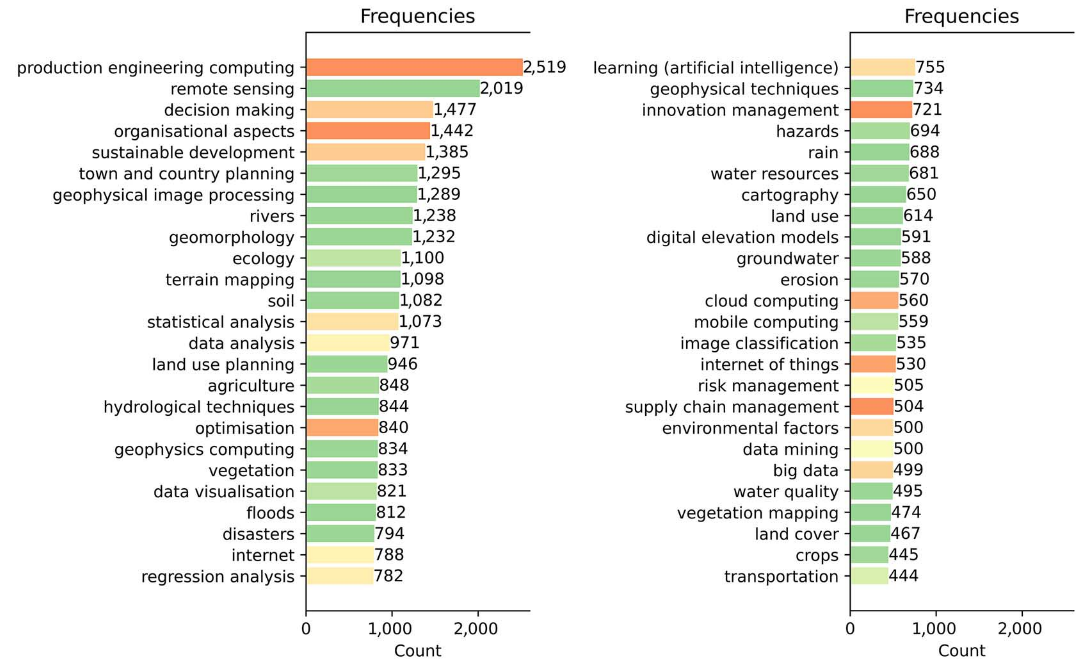
MFG clusters, shown as shades of yellow, because the two root terms in MFG are heavily influenced by one another and share lower level indexed terms. This can be seen by the fact that the two root terms are quite proximal to one another in the layout. That being said, there are many more indexed terms in the MFG cluster, which could indicate that the research community exhibits much more disparate breadth representing individual research subfields compared with the GIS&T community. That being said, the relative "tightness" of the GIS&T cluster could bode well for manufacturing research teams to interface with GIS&T experts.

To identify research terms and concepts as potential anchor points for the two communities to converge, we dive deeper into the "yellowish" indexed terms. To begin, figure 3 shows the top 50 most frequently occurring terms across the data set, excluding the 3 root search terms from Inspec. Color coding, as with all charts in this paper, adheres to the aforementioned histogram (fig. 1). To reiterate, terms that have fewer occurrences do not necessarily indicate lack of coverage in either research coverage. It could simply mean that the terms themselves are not well seeded in the Inspec database. "Production engineering computing" and "remote sensing" exhibit the most frequently occurring tags across records from MFG and GIS&T, respectively.

Terms that exhibit similar coverage across both communities include "data analysis," "internet," "regression analysis," "risk management," and "data mining," all of which are rather popular and widely captured methods and interests in modern research programs.

Figure 4 presents what we consider to be trends established across both the GIS&T and MFG communities. We identified trends in two ways. Firstly, we uncovered indexed terms that score between −0.5 and 0.5 in the

FIG. 3 The top 50 terms (with respect to quantity) and their relationship to GIS&T or MFG community. Orange represents terms and relationships that solely fit within manufacturing systems and industries. Green represents terms and relationships that solely fit within geospatial information systems. Yellow shows the overlap.



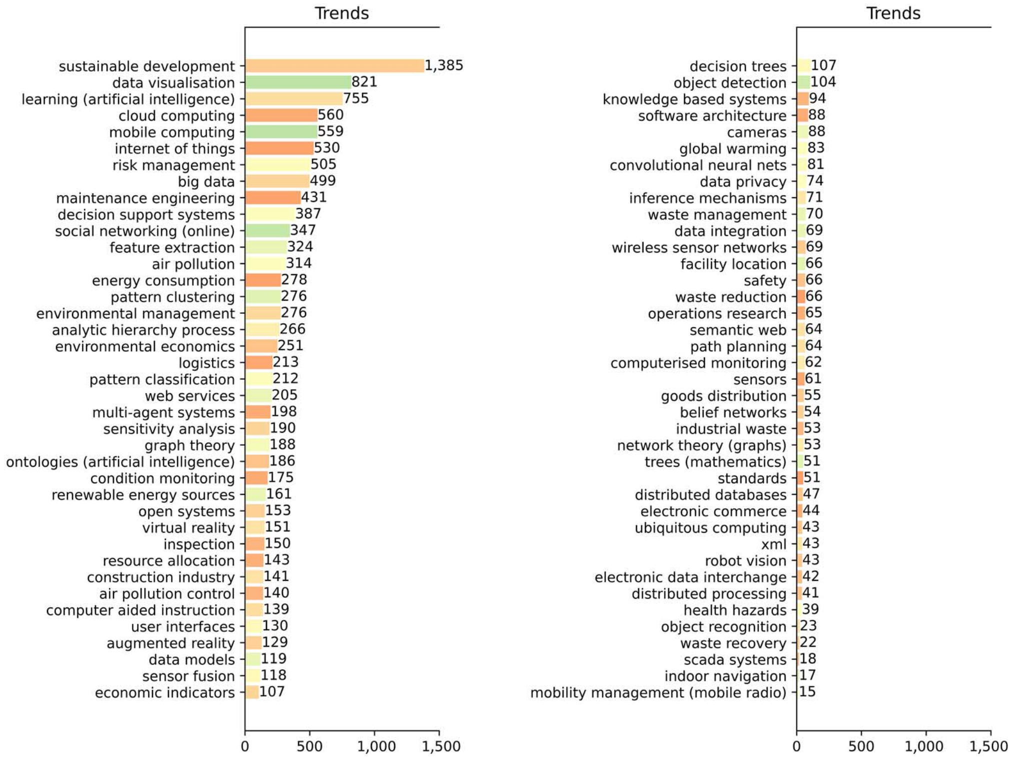
presented metric and exhibit at least 15 appearances across the data set. Secondly, we manually screened other indexed terms that might not land within the scoring bounds yet exhibit a relatively high number of occurrences in both MFG and GIS&T communities. The top five trends in terms of total occurrences exhibit research trends across the general scientific community, namely "sustainable development," "data visualization," "learning (artificial intelligence)," "cloud computing," and "mobile computing." If we look closer at the identified terms, we can uncover research topics that sit closely to the overarching research field of Industry 4.0. From our perspective, spatial computing has an immense potential to advance large-scale manufacturing systems. These terms include Internet of Things, web services, ontologies, VR, AR, and standards.

Furthermore, we point out additional terms of interest that could be justified as explicit trends across the two communities. We tag these terms as "opportunities." Figure 5 depicts potential directions or additional anchors for the two research communities to converge. Here, we listed the top 23 terms that are opportunities for SM but originate from the GIS&T community. In addition, we removed terms that are solely related to land management or geography, such as "rivers," "remote sensing," and "geophysical image processing." The results clearly indicate that there are several topics on the horizon that could be beneficial for both fields. Among those terms are "hazards," "image classification," "building management systems," "spatio-temporal phenomena," "location-based services (LBS)," and "text analysis." Each of these terms demonstrate a convergence of research between GIS&T and SMS. For example, to properly identify and avoid "hazards" in a manufacturing environment, defining spatial context and consistent reporting of the location of hazardous objects is required.

QUESTIONNAIRE RESULTS

In this section, we present the details of the participants of the questionnaire itself and their responses in detail. The purpose of the questionnaire is to better position the findings of the meta-analysis and uncover feasible paths forward. We have separated the contents in two consecutive subsections.

FIG. 4 Identified research trends that exhibit significant contribution to both communities, i.e., GIS&T and SMS.



Details of the Respondents

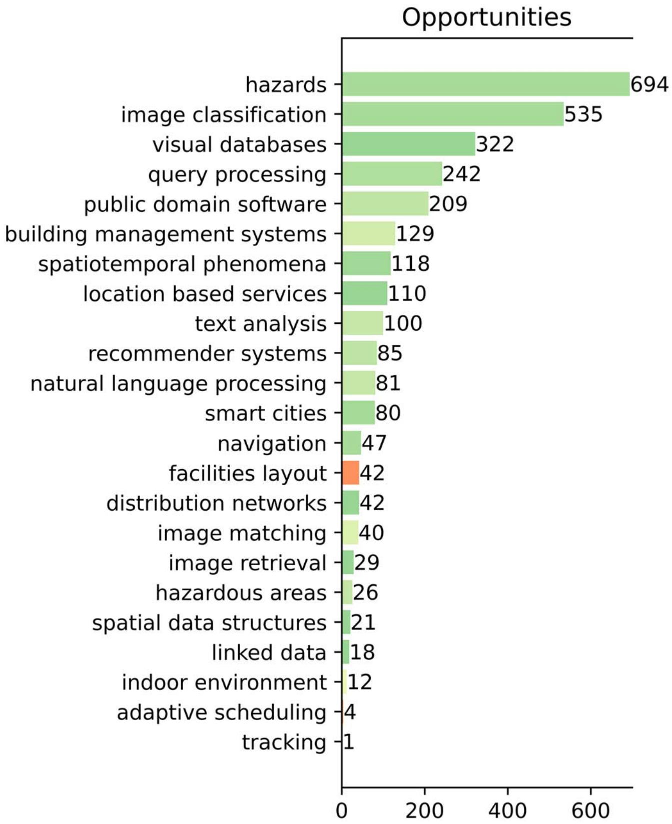
The respondents exhibited diverse backgrounds ranging between Computer Science, Engineering (Computer, Technology, Design), Geography, Geospatial Science, and Industrial Engineering. In addition, the current job titles of the respondents reflect this broad range as well as the respondents' positions include research scientist, research manager, manufacturing engineer, geospatial scientist, business executive, and computer programmer. All survey participants have an academic education with degrees higher than a bachelor's degree. The average age of the respondents is 39.9 ± 15.38 years. The gender balance of the respondents is shifted toward the male gender, having a share of 53.27 %. In total, 14.29 % respondents are female, and 32.14 % did not reveal their gender. The origin of the respondents includes Austria (11 persons), Australia (3 persons), United States (3 persons), and United Kingdom (1 person). Seven respondents did not reveal their country of residence. The professional background of the respondents is as follows: 38.47 % have a background in geography or geospatial science, whereas 34.61 % have an engineering background (computer, industrial engineering, or similar) and 26.92 % did not reveal their background. Based on these survey responses, the balance between the geospatial/geography cohort and engineering cohort is relatively close. We can conclude that results seem to not be biased by an overrepresentation of one group over the other.

Survey Results

We procured 28 responses in total, and the complete results are included in the Supplemental Materials. In this subsection, we focus on the main results of the survey in both a quantitative and qualitative way. First, we would like to elaborate on the quantitative findings, followed by some more qualitative insights. The reported percentages do not always add up to 100 % because multiple choice responses are possible. In these cases, the percentage represents the share of respondents who have selected a specific answer.

FIG. 5

Identified opportunities based on the described methodology. Researching working across SMS and GIS&T should consider these terms as future research avenues.



Generally speaking, the respondents show a mixed usage of Geospatial Technologies in Industry 4.0 environments and scenarios. Most responses report on the usage of GIS&T for asset localization and mapping (55 %), mapping of physical movement of production assets (33 %), sensor localization (33 %), for dashboard purposes (22 %), and augmented and virtual reality (22 %). Smart maintenance was only chosen by one respondent.

Question #12 was targeted at understanding the current status of GIS&T data integration in SMS. In total, 30.77 % of the respondents are integrating GIS&T data with the help of their exact coordinates. Any other spatial anchor like location names, temporal markers, or camera feeds are not used, according to the respondents.

Currently, the standards used are CityGML (62.5 %); Web Mapping Service (62.5 %); Web Feature Service (50 %); Point Cloud Formats, like the Adobe Flash Lite Sound Bundle Format, the Point Cloud Data File Format, or the LASer File Format (50 %); and SensorThings API (50 %), followed by Web Processing Service, IndoorGML, Compressed Square Wave (CSW) files, and Geography Markup Language. The community uses standards mostly for modeling of indoor spaces (and digital twins) and research purposes. Concerning the usage of standards, we asked about advantages and barriers for using standards. The respondents mentioned challenges related to complexity with respect to difficulties in implementing standards. One such opinion reflected that standards do not often relate to their organizations' practical requirements.

Regarding the level of data collection for SM facilities, we see that most data are collected at the ANSI/ISA-95, Enterprise-Control System Integration Level 1 (I/O Link, DeviceNet, Sensors) (72 %), followed by ISA-95 Level 2 (e.g., supervisory control and data acquisition, computer numerical control, human-machine interface) (45 %), ISA-95 Level 3 (e.g., Warehouse Management System (WMS), manufacturing execution system, laboratory information management system) (27 %), ISA-95 Level 4 (e.g., enterprise resource planning, application portfolio optimization, Logistics) (18 %). Lots of data are available at ISA-95 Levels 0 and 1 are often collected at significant scale. Yet, relating those data to higher enterprise levels remains challenging with little guidance.

Looking into participants' envisaged future state of GIS&T and SMS, we were specifically curious about the future application areas for both areas. Most answers mentioned asset localization (87.5 %), maintenance (87.5 %), incident management (62.5 %), and asset transportation (indoor) (50 %). To a lesser degree, warehouse picking (25 %) and production performance monitoring (37.5 %) were mentioned as well.

In a follow-up question, we were interested in the barriers to the envisaged future state of GIS&T and SMS. The reasons are as follows:

- availability of indoor positioning systems (75 %),
- accuracy of indoor positioning systems (62.5 %),
- data interoperability (62.5 %),
- system interoperability (62.5 %),
- lack of technical experienced staff (50 %),
- costs of indoor positioning (37.5 %),
- latency (25 %), and
- data storage capacity (12.5 %).

When evaluating the responses in concerning their qualitative content, we selected two types of "typical" user groups in our survey and looked at their responses as a group. From the survey participants, their background and current affiliation, we basically have two groups:

- Geospatial science, defined as people having an educational background in GIS&T, related fields, or both or working in the geospatial industry/academia
- Industrial engineering, defined as people having a background in industrial engineering, manufacturing engineering, or both working in the respective field(s) as of now

The two groups exhibit different response patterns. The responses from the geospatial science group express that industrial data captured from the manufacturing environment are collected up to ISA-95 Level 3. Additionally, they generally regard indoor data as being GIS&T data of distinct objects, and, in turn, georeferencing makes use of X/Y/Z coordinates. The combination of SM and GIS&T may be most beneficial for the design of efficient processes and the optimization of transport processes. This is realized using a wide range of contemporary geospatial standards (WMS, CSW, IndoorGML, etc.), whereas the standards from the SMS world are mostly neglected (except for OPC Unified Architecture). The responses show us why those standards are so broadly neglected. In the respondents' eyes, the SMS standards are complex, difficult to work with, and burdensome to implement. According to the responses of the geospatial science group, the barriers for flourishing the integration of GIS&T and SMS are the lack of (1) data and system interoperability, (2) availability of indoor positioning and accuracy thereof, and (3) technical staff.

The responses from the industrial engineering group are as follows. Data are collected up to ISA-95 Level 4, whereas the data are regarded as rather poor in terms of data quality. The indoor data are predominantly computer-aided design (CAD) data of indoor objects (i.e., CAD-based geometries), which are georeferenced with the help of X/Y/Z coordinates. The implementation of GIS&T and SMS may be beneficial to realize cost savings, model, and optimize transportation processes as well as conduct asset localization and mapping. The industrial engineering group does not widely use SMS standards and neglects standards present in the geospatial industry. Respondents cited that in their opinion such standards are too complex, costly, and challenging to implement. The responses of the industrial engineer group see that SMS and GIS&T may have a future role in asset localization and transportation, incident management, and warehouse picking as well as performance monitoring. Nevertheless, there are a number of barriers, according to the responses, including the following: data and system interoperability, latency, availability of indoor positioning systems, costs of indoor positioning systems, IT cooperation, and lack of experienced staff. Some responses indicate that problems might lie in the transition to smart (or digital) manufacturing. For example, one respondent indicated that "IT organizations are too slow to let teams adopt new technologies and give automated access to data sources. No Industry 4.0 solution is scalable if it takes humans clicking screens." In addition, respondents indicated that deployed devices are often obsolete and are not capable of handling Industry 4.0 applications.

KEY TAKEAWAYS

Based on the literature meta-analysis, we identified seemingly promising opportunities for the research community to pursue. We classify the identified opportunities (in fig. 5) into seven higher level categories, including the following:

- Image analysis: image classification, image matching, image retrieval
- Databases and software engineering: visual databases, query processing, public domain software
- (Geo-)semantics and ontologies: spatiotemporal phenomena, text analysis, recommender systems, natural language processing, linked data
- Modeling indoor space: building management systems, facilities layout, indoor environment
- Spatial optimization: navigation, distribution networks, adaptive scheduling
- Geographic Information systems: location-based services, smart cities, spatial data structures, tracking
- Other topics: hazards, hazardous areas

Note that many of these research topics are already heavily covered in manufacturing, yet they do not appear be well represented in the Inspec database. This issue is quite common and in itself could present a barrier for research communities to closely work together. In the age of digitization, proper tagging/labeling of publication records is critical for disparate communities to find common topics to which they can contribute. Nevertheless, regardless of the errors and omissions in the metadata of publication records, similar research priorities were presented in the survey results.

The survey revealed that most practitioners in the field of SM are not fully aware of the potential of Geographic Information technology at the moment and do not necessarily know about standards in the field of geoinformation (GI). Similarly, the survey results suggest that experts in the field of GI are not familiar with relevant standards in the field of SM.

As stated by most survey participants, the primary barriers for the utilization of GI technology in SM are mostly due to the lack of the following:

- Indoor positioning systems
- Accuracy of indoor positioning
- Data and system interoperability
- Technical experienced staff

The reasons why standards are avoided by SM companies are manifold. Responses tell us that companies think that standards would be too complex or challenging/costly to implement or that they do not fully address the needs of the company.

Nevertheless, most companies plan to use Geographic Information technology in their SM road map (implicitly or explicitly mentioned). Considering the use cases in the responses that range between asset localization, transportation, incident management, and especially maintenance, there appears to be significant potential to apply GIS-related technology in manufacturing facilities.

Discussion on Research and Standards Opportunities

In this section, we highlight some technological priorities that need to be addressed in order to advance spatial perspectives for Industry 4.0 further. We elaborate on some technological topics and their relation to each other and suggest an initial plan for the GIS&T and SMS communities to adopt. The discussion here is fueled by the results of the survey (see "Survey Results" section) and the literature meta-analysis (see "Key Takeaways" section). The identified weaknesses—especially by the survey results—are the first key items on the roadmap, followed by "exploiting" the opportunities identified by the literature meta-analysis.

TECHNOLOGICAL PRIORITIES FOR GIS&T AND SMS FIELDS

The following list of technological deep dives and in-depth descriptions is intended to provide an overview of technologies that will help bridge and close the gap between GIS&T and SMS.

IndoorGML

The OGC standard[41] describes indoor space accordingly and provides a spatial reference for features present in the modeled indoor space. In contrast to outdoor space, indoor space requires the modeling of complex constraints, e.g., staircases, elevators, corridors. The standard consists of five parts/components: cellular space, semantic representation, geometric representation, topological representation, and multilayered representation. Cellular space represents the smallest modeled structural unit. The semantic representation is intended to provide additional information on the cell and to define the connectivity between cells. The geometric representation is intended to define the geometry (in accordance with ISO 19107:2019, *Geographic Information — Spatial Schema*[52]).

The topology is required to define topological relationships of indoor objects using the node-relation graph without the necessity of storing the geometry together with the topology. The multilayered representation is used because indoor space can be covered by multiple cellular spaces (e.g., Bluetooth, Wi-Fi, topographic space [rooms, corridors]).

Knowledge Representation Using Ontologies and GeoKnowledge Graphs

GeoKnowledge Graphs (GeoKGs) are regarded as symbolic representations of geospatial knowledge and are at the core of GeoAI and facilitate intelligent applications such as geospatial data integration and knowledge discovery. Geospatial data play a vital role in the Linked Open Data cloud, an open-sourced cross-domain (Geo-)Knowledge Graph, because the spatiotemporal dimension is essential for describing events, people, and objects. An ontology with respect to computer science is a "formal, explicit specification of a shared conceptualization."[53]

Ontologies allow the formulation of abstract concepts as formal specification, which are in turn machine-readable and define concepts and terms even if they are from different domains. Both the SM and GIS&T communities have established significant efforts in the development and use of ontologies. Leveraging existing efforts will expedite new perspectives, such as the convergence of GIS&T and SM.

GeoAI

GeoAI, as an interdisciplinary field of Geographic Information Science and artificial intelligence (AI), combines the idea of developing and utilizing AI techniques in geography and earth science.[4] Hence, GeoAI is based on the recent progress in AI techniques in conjunction with available high-quality data and advances in hardware and software efficiency. The availability of spatial data, novel methods in machine learning, and technical language processing are reshaping the environment of spatial analysis. Again, AI, NLP, and other data science–related techniques are already pervasive in SMS. Establishing the proper links between both community efforts is vital for success.

VR/AR

Advanced visualization modalities, such as AR and VR, are of particular importance for SMS, evidenced by a number of recent publications.[54–59] According to Baroroh, Chu, and Wang,[56] AR is intended to support the collaboration between humans and intelligent machines in real time in a manufacturing environment. According to the study,[56] 22 % of the AR functionalities are for object recognition and 15 % for positioning, which both can reduce the cognitive workload of a user. Similarly, Uva et al.[55] report that AR coupled with spatial information is significantly better than contemporary AR. The results show that the spatial AR helps to reduce completion times (reduction of 20.3 % in overall completion time) and error rates (83.3 % fewer errors with spatial AR). Hence, AR and VR as part of SMS can help to make manufacturing processes more efficient. Note that a significant number of standards that enable spatial computing and spatial AR are born from the GIS&T community, e.g., OGC's GeoPose.[60] To construct more robust industrial AR/VR experiences for manufacturing, adhering to best practices from the geospatial standards community is important.

INTEGRATED VIEW AND ROADMAP

In the section "Technological Priorities for GIS&T and SMS Fields," we elaborated on a number of technological advancements that may help to advance the integration of SMS and GIS&T. First and foremost, to be able to make use of the spatial dimension, manufacturing facilities need to be represented in a digital and spatial way. Hence, the OGC IndoorGML standard helps to model and exchange relevant spatial information on the indoor space under review. The standardized indoor representation is of especially particular interest in terms of interoperability because one single indoor representation could be the basis for several SMS applications. In particular, in VR and AR applications for manufacturing purposes, any application dealing with (Geo-)AI could benefit from a standardized spatial representation of manufacturing facilities. An accurate representation of the indoor space is beneficial for accurate and precise indoor positioning systems and wayfinding instructions in an indoor environment.[61,62]

In addition, knowledge representations and knowledge graphs are a way to facilitate interoperability between different software systems and help to integrate both worlds: GIS&T and SMS. However, GeoKGs heavily rely on an accurate spatial representation of the environment under review. GeoAI, as defined previously, may utilize both the standardized representation of the indoor space and their properties as GeoKG. GeoAI may help to detect (spatiotemporal) trends and hidden patterns in manufacturing data with the help of AI methods. One effort of note in the manufacturing research community is the Industrial Ontology Foundry (IOF) (https://www.industrialontologies.org/, accessed July 2022), a consortium focused on curating mergeable industrial ontologies. One idea would be to contribute a GeoKG focused on industrial environments to the IOF. This could ignite "sandboxing" (or prototyping) efforts to produce demonstrations that exhibit the advantages of introducing spatial data into manufacturing use cases.

For visualization and communication purposes of manufacturing-related data, the map metaphor may contribute to the SMS field. This is underpinned by the argument that a map-based representation of production-related data and the results of incident analyses or layout planning can easily be shared and understood by all related stakeholders. A map metaphor could contribute to the prognostics and health management community. For example, failure modes in manufacturing facilities often relate to proximal systems, such as heating, venting, and air conditioning. Understanding historical effects of spatial layout of equipment can facilitate better design and planning. A roadmap for the (further) integration of GIS&T and SMS might appear as follows (see figs. 6 and 7):

Develop an approach to implement an indoor representation of the manufacturing environment or migrate any (proprietary) representation (e.g., CAD) of the indoor environment into a standardized spatial data format that includes semantics, preferably OGC IndoorGML.[41] Note that IndoorGML in its current form does not natively accept 3-D scans as input. Currently, 3-D scans represent quite a common practice for instantiating a computer-interpretable representation of an indoor manufacturing facility. Addressing the registration issues between CAD-like representations of indoor spaces with point cloud (or mesh) reconstructions would better facilitate proper use.

Develop and implement approaches to identify implicit and explicit spatial information in manufacturing systems. Implicit spatial information can be device names, corridor names, or room names, whereas explicit spatial information mostly deals with coordinates in a defined coordinate reference system. Existing standards, like IndoorGML, support the representation and storage of indoor structures like rooms, hallways, and elevators and the connection between those elements with the help of coordinates. Research should concentrate on methodologies to make the spatial dimension of manufacturing data explicitly available, e.g., by georeferencing methodologies, or semantic enrichment and analysis of existing manufacturing data.

FIG. 6 The research and development items of the roadmap to integrate GIS&T and SMS. The topics centered around SMS are single R&D items that can be developed and integrated in SMS as part of the roadmap.

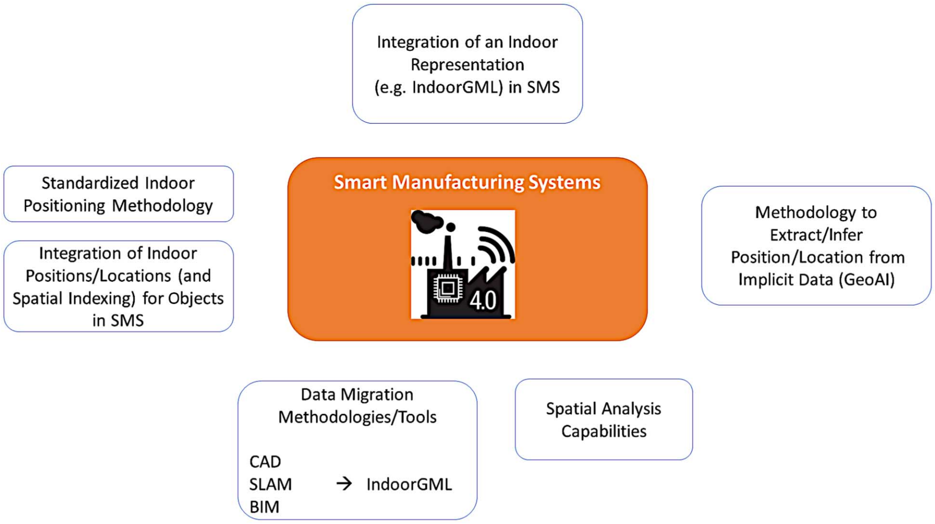
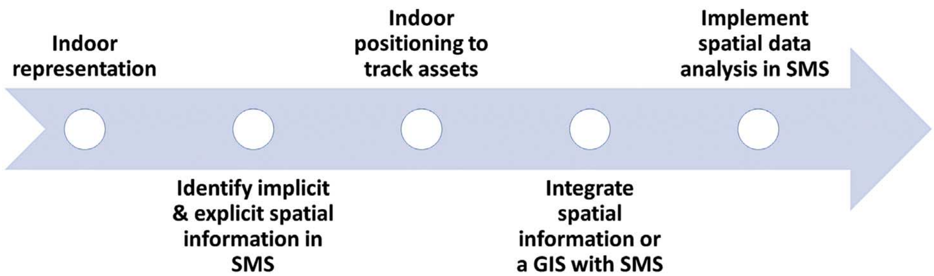


FIG. 7 The timeline of the R&D roadmap to further integrate GIS&T and SMS. The research items should be addressed subsequently in order to fully utilize the analytical power of GIS&T in SMS.



Develop standardized indoor positioning methodologies to track assets or devices in the manufacturing environment (not necessarily using a highly sophisticated system; ZigBee or Bluetooth Low Energy may fulfill the indoor positioning accuracy requirements or you can implement a highly accurate ultra-wide band solution) or both and connect the positioning solution to the SMS. Currently, there is a lack of open data sets that provide baseline capability measurements of different localization technologies. Addressing this gap should be a primary focus of this particular task. Nevertheless, several vendors of indoor positioning technologies have entered the market and provide indoor positioning solutions for manufacturing purposes at a competitive price range (https://www.zebra.com/us/en/products/location-technologies.html, accessed July 2022; https://ubisense.com/, accessed July 2022).

Connect SMS with spatial information, a GIS (and vice versa), or both to be able to georeference, spatially analyze, and visualize SMS data. Using case identification in this task is critical. Insights drawn from relating spatial data to industrial data are dependent on proper problem identification and goal setting.

Implement spatial data analysis capabilities in SMS. These systems may utilize spatiotemporal analysis and GeoAI methods to detect patterns in the data at hand. Again, manufacturing analytics, at this point, are pervasive in practice.

The preliminary roadmap (see fig. 7) presents a proposed strategy to implement an integrated SMS and GIS&T solution for a given manufacturing environment to be able to analyze spatial patterns in production-related data. In figure 7, the temporal sequence of the integration tasks is laid out. Starting from an indoor representation, to identify spatial information currently present in SMS, we suggest implementing an indoor tracking system. Having the spatial data (i.e., historic trajectories and current positions) of production assets enables the integration of spatial information or a Geographic Information System directly in an SMS. This paves the way to implement and integrate spatial analysis functionalities directly in an SMS. Such integration roadmaps for coupling GIS with IT solutions for different industry sectors have been developed and published to date.[63–65]

On top of that, one could always add VR and AR that might support industry-driven use cases, e.g., maintenance operations. Critical for a successful integration of GIS&T and SMS is the ability to connect SMS entities with spatial data (or positions at least). This is highlighted in the results of the survey and the algorithmic literature review.

Conclusion

The paper elaborates on the integration of GIS&T and SMS. In particular, the paper is intended to evaluate (1) the possibilities of a successful GIS&T and SMS integration and (2) obstacles that hinder the integration of both fields. The methodological approach includes an algorithmic literature analysis and a survey with experts in the field.

The results reveal that both fields have interesting concepts that could mutually support each other and that SM could benefit from GIS&T technologies in particular. Nevertheless, the expert survey revealed that there are several barriers to integrate GIS&T and SM nonstandard data elements and systems interfaces, including differences in positioning accuracy requirements and the complexity and cost of implementing standard interfaces, to name the most prominent ones. Looking at the results, the standardization perspective is most striking because there seems to be a need to mutually learn and understand the standardization initiatives present at SM and GIS&T. This is especially true because respondents from each world do not seem to be familiar with standardization from the other discipline. This is particularly noticeable because SM still utilizes CAD data formats, which can hardly be integrated in VR and AR applications or digital twins or utilized for GeoAI analyses.

This leads to a number of identified opportunities and future research directions for the integration of GIS&T and SMS. The algorithmic literature analysis and the survey with experts revealed fields like image analysis, databases and software engineering, (geo-)semantics and ontologies, modeling indoor space and spatial optimization, and GIS&T in general (i.e., location-based services) to be further integrated in SM. In order to foster the integration of GIS&T and SM, the paper proposes a simple roadmap that advocates for a standardized spatial representation of the indoor space (e.g., IndoorGML) under review as the basis for all further "endeavors." Nevertheless, the integration of SM and GIS&T has great potential and could reveal hidden patterns in production-related data by using GeoAI or visualize them using the map metaphor or in VR and AR.

Supplementary Materials

Supplementary information for this paper is available at https://github.com/Geoinfo-TUGraz/SMS_GIS_ASTM_Journal/blob/main/survey_print%20(1).pdf and https://github.com/Geoinfo-TUGraz/SMS_GIS_ASTM_Journal/blob/main/Umfrage_558491_Geospatial_Data_Geographic_Information_Systems_and_Smart_Manufacturing%20(1).pdf.

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