

Visualization for Simulation-Based Decision Support in Manufacturing

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Dissertation

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Abstract

Nowadays, the increasing demand for ever more customizable products has emphasized the need for more flexible and fast-changing manufacturing systems. In this environment, simulation has become a strategic tool for the design, development, and implementation of such systems. Simulation represents a relatively low-cost and risk-free alternative for testing the impact and effectiveness of changes in different aspects of manufacturing systems.

Systems that deal with this kind of data for its use in decision making processes are known as Simulation-Based Decision Support Systems (SB-DSS). Although most SB-DSS provide a powerful variety of tools for the automatic and semi-automatic analysis of simulations, visual and interactive alternatives for the manual exploration of the results are still open to further development.

The work in this dissertation is focused on enhancing decision makers' analysis capabilities by making simulation data more accessible through the incorporation of visualization and analysis techniques. To demonstrate how this goal can be achieved, two systems were developed. The first system, *viPhos* – standing for visualization of Phos: Greek for light –, is a system that supports lighting design in factory layout planning. *viPhos* combines simulation, analysis, and visualization tools and techniques to facilitate the global and local (overall factory or single workstations, respectively) interactive exploration and comparison of lighting design alternatives. The second system, *STRAD* - standing for Spatio-Temporal Radar -, is a web-based systems that considers the spatio/attribute-temporal analysis of event data. Since decision making processes in manufacturing also involve the monitoring of the systems over time, *STRAD* enables the multilevel exploration of event data (e.g., simulated or historical registers of the status of machines or results of quality control processes).

A set of four case studies and one proof of concept prepared for both systems demonstrate the suitability of the visualization and analysis strategies adopted for supporting decision making processes in diverse application domains. The results of these case studies indicate that both, the systems as well as the techniques included in the systems can be generalized and extended to support the analysis of different tasks and scenarios.

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Introduction

1.1 Motivation and Problem Statement

Nowadays, the increasing demand for ever more customizable products has emphasized the need for more flexible and fast-changing manufacturing systems. In this environment, simulation has become a strategic tool for the design, development, and implementation of such systems. Simulation represents a relatively low-cost and risk-free alternative for testing the impact and effectiveness of changes in different aspects of manufacturing systems.

Simulation has become very popular for tackling problems such as material flow, production scheduling, factory layout planning, ergonomics, and other aspects regarding sustainable manufacturing. Thus, systems that can cope with the large amount of data resulting from simulations and at the same time assist experts in the decision-making process are required. These systems are known as Simulation-Based Decision Support Systems (SB-DSS). Although most SB-DSS provide a powerful variety of tools for the automatic and semi-automatic analysis of simulations, visual and interactive alternatives for the manual exploration of the results are still open to further development. This is the case with the evaluation of indoor environment design and assessment in factory layout planning.

Currently software tools oriented to the simulation and later evaluation of indoor environment conditions such as lighting, temperature, or airflow within a factory floor come from the architecture domain (e.g., building performance simulation tools, lighting design software). While these tools provide the basis for the early design of factory layouts, most of them do not provide the visualization and interaction capabilities for detailed comparison and evaluation of multiple scenarios.

1.2 My Contributions

The main contributions of this dissertation are comprised in the design and development of a SB-DSS for lighting design in factory layout planning named *viPhos* – standing for visualization of Phos: Greek for light –. *viPhos* combines simulation, analysis, and visualization tools and techniques that facilitate global and local (overall factory or single workstations, respectively) interactive exploration and comparison of lighting design alternatives.

The main feature of this system is the interactive visualization and analysis module that enables the comparison of multiple lighting design alternatives and evaluates them against well know standards for lighting in industrial settings. Some characteristics of *viPhos* include:

- *Compliance with standards.* To validate the compliance with standards as well as to facilitate the local and global evaluation of lighting alternatives, *viPhos* incorporates a new element called the “requirements grid”. This grid covers the area of the factory layout and stores at each vertex location, a set of scalar values representing information about the minimum illuminance requirement in addition to custom fields to determine, for example, a priority/importance weight for specific locations within the factory floor.
- *Integration of open-source tools for simulation.* One of the design principles that drove the design of *viPhos* was the use of open source tools and libraries. Therefore, RADIANCE [117], a physically-based rendering system developed by Greg Ward Larson at the Lawrence Berkeley National Laboratory, California along with Blender[15], and VI-Suite 0.3 add-on for Blender [103] are used to perform the lighting simulations.
- *Analytic tools.* *viPhos* relies on a suite of data analytic tools based on statistical image processing techniques. Operations such as image subtraction, mean absolute deviation, and weighted difference are included in the system. In addition, *viPhos* applies novel metrics incorporating illuminance field derivatives information for the quantitative analysis of light quality.
- *Visual Exploration Interface.* *viPhos* incorporates a visual exploration interface including 3D visualization and abstract visualization to facilitate the analysis of raw and post-processed simulations. The interface has three different views that support different phases of the decision making process.
 - Phase 1: Exploration of raw simulation results.
 - Phase 2: Comparison and validation of alternatives against standards.
 - Phase 3: Overall analysis of alternatives.

To demonstrate the functionality of the system, two case studies are presented. The first one refers to the lighting design for a plastic injection molding manufacturing cell. This case uses the European standard “Light and Lighting - Lighting of Workplaces — Part 1: Indoor Work Places. EN 12464-1” as reference. The second case study is the result of a collaboration with the AHMCT (Advanced Highway Maintenance and Construction Technology Research Center) center at UC Davis which considers the lighting design for a road work zone. The lighting recommendations

provided in the “California Manual on Uniform Traffic Control Devices” [108] are used as reference standard for this case study.

In this dissertation, I also considered the enrichment of a SB-DSS by extending its capabilities to integrate non-simulation data. An example of such kind of data would be spatio-temporal event data, for example, historical event registers for all the stations involved in a manufacturing cell (e.g., machine status, machine maintenance alarms, etc.). *STRAD*, a web-based system and library enabling the visualization and interactive exploration of this kind of data was developed for this purpose. As a result of the collaboration with the engineering school at University of Los Andes (Bogota, Colombia), two case studies involving this type of data in the application domain of urban planning were implemented. Here, the visual comparison among multiple urban areas is also the key feature. In addition, a proof of concept demonstrating the use of *STRAD* for the analysis of manufacturing process control data for quality assurance validates the applicability of the system and library in another field of manufacturing.

The results presented in this dissertation show the advantages of introducing and applying existing and novel visualization techniques for supporting decision-making processes in different application domains such as: simulation-based factory layout planning, road construction and maintenance, urban planning, and manufacturing process control for quality assurance. The two presented software systems, *viPhos* and *STRAD*, advance upon existing approaches as they focus on enhancing the visual comparison and interactive exploration of data. The case studies presented for both systems helped experts to gain insights about the specific data sets.

On one hand, *viPhos* introduces visualization and analysis capabilities currently not available in the state-of-the-art lighting simulation software. In addition to these capabilities, it facilitates the evaluation of new performance metrics based on the derivatives information of illuminance fields for the quantitative evaluation of light quality in industrial environments.

On the other hand, *STRAD* explores the visualization and direct manipulation of event data through a visual querying interface. This system exploits the advantages of visual exploration tools and visual query systems from a multilevel perspective (multiple spatial/attribute scales and temporal resolutions). This multilevel approach favors the comparison of events' occurrence at different times and locations as well as the intuitive aggregation of data in the spatial/attribute and temporal domains.

1.3 Thesis Structure

Chapter 2

This chapter provides the theoretical framework of decision support systems and simulation-based decision support systems in the field of manufacturing. Besides providing a general overview to the topic and the state of the art in this field, contributions and opportunities from other research fields such as visualization, and particularly, visual analytics for the support of decision making in manufacturing is also highlighted. In addition, this chapter introduces an extension to a previously developed user-centered methodological approach for guiding the design, implementation, and evaluation of decision support systems.

Chapter 3

Starting with Chapter 3, my results and contributions will be presented. The content of these chapters is summarized here. This chapter introduces *viPhos* a simulation-based decision support system for lighting in factory planning. It assists factory planners in the evaluation of lighting alternatives to select the best fitting configuration concerning the compliance with a determined standard. *viPhos* combines simulation, analysis, and visualization tools and techniques that facilitate global and local (overall factory or workstation/structural areas, respectively) interactive exploration and comparison of lighting alternatives. The following subsections present the context of use of the system as well as implementation details and case studies in factory planning and road construction work zones.

Chapter 4

This chapter presents *STRAD* (Spatio-Temporal Radar), a web-based interactive visualization system created for the exploration of spatio/attribute-temporal event data. *STRAD* is designed as a visual query interface that provides an intuitive way for the interactive exploration of temporal and spatial/attribute patterns. In contrast to other developments in this direction, *STRAD* offers a multilevel exploration approach (both in the spatial/attribute and temporal dimensions) that allows to keep the context of the data while querying it. In addition, *STRAD Wheel*, a web-based library that includes the visualization and interactive exploration capabilities of the temporal dimension was derived as a sub-product of *STRAD* and is currently distributed as an open source JavaScript library under a MIT license for its use within other application domains.

Chapter 5

In this chapter, the results of this dissertation are summarized and the main highlights of the two developed systems: *viPhos* and *STRAD* are outlined. This chapter addresses directly the questions: what can be done now that was not possible before?, and how

does this work supports and improves the analysis of the data in the manufacturing domain as well as in the other explored domains?.

Simulation-Based Decision Support Systems (SB-DSS)

From the early 1960s, an important effort has been made to formalize the theoretical foundations and application cases of Decision Support Systems (DSS). As a result, several frameworks that aim at categorizing these systems with respect to different criteria have been formulated. For instance, Alter [3] developed a process-oriented framework while Sprague [105] developed a more technology-oriented framework. As the scenarios that require decision support become ever more complex in terms of data, models, and knowledge, these frameworks have been consistently extended and adapted to reflect the evolution of the needs and requirements for such systems. Power [80] went a step forward in this direction and proposed an extended framework that allows the classification of DSSs with respect to two dimensions: 1) dominant component driver and 2) deployment and enabling technology. The clear distinction between the types of decision support systems not only facilitates the establishment of common requirements and tasks that should be supported by each type of system but also facilitates the communication between users and developers of such systems.

Simulation-based decision support systems (SB-DSS), according to Power's framework, fall into the category of model-driven decision support systems in the primary dimension, and task-specific in the secondary dimension. Having a major comprehension of the characteristics inherent to this type of DSS is essential in order to develop and apply techniques that ease the design, implementation, and evaluation of these systems.

This chapter provides a general overview to decision support systems, simulation-based decision support systems, and their applications in the manufacturing domain. The contribution of the other research fields such as visualization, and particularly visual analytics for the support of decision making in manufacturing is also highlighted. Furthermore, the challenges of the integration of visualization support for SB-DSSs are outlined and a generalized user-centered methodological approach for guiding the design, implementation, and evaluation of decision support systems is presented.

2.1 Decision Support Systems (DSS)

Decision-making is a process that involves the selection of an alternative, among a set of alternatives, which defines a course of action leading to the achievement of an objective(s) in a particular situation. The success of this process relies on the correct and deep understanding, by the decision makers, of the big picture of the situation, its environment, the possible courses of action, and the objectives that must be fulfilled. The construction of this environment for decision making involves the consideration of a complex and large amount of data and knowledge from different application domains. In order to cope with this fact, computer-based systems have been introduced within the decision making process. These systems are known as Decision Support Systems.

As defined by Crossland [28], a DSS is “a computer-based system that combines data and decision logic as a tool for assisting a human decision maker”. Crossland also highlights that DSSs are not systems for automating decision making processes (they do not suggest or make concrete decisions), but instead, they assist decision makers by analyzing and presenting the available information in a more intuitive way.

The methods, technologies, and strategies applied for the design and implementation of a DSS vary in regard to different criteria. For example, the main technology driving the development of the system, the type of data they process (e.g., real-time, historic, simulated, etc.); the application domain they support (e.g., geospatial analysis, production systems, financial analysis, etc.); or type of decision making process to be assisted (e.g., collaborative, individual, etc.). Several researchers have focused in making a clear distinction of these categories as they help in the establishment of requirements specific to each type of DSS. Although multiple classification frameworks have been developed, this remains an evolving task as new technologies, information, and decision support needs emerge.

Sprague [105] proposed a framework to organize the knowledge about DSSs. In his work, he proposed a framework composed of two blocks. The first block classifies the knowledge about DSSs with respect to three aspects: 1) technological level, 2) developmental approach, and 3) the roles of the users and developers of the DSS. The second block of the framework is dedicated to draft strategies for the evaluation of DSSs in practice. Although this is a broad approach that involves the entire process of conceiving and evaluating a DSS, the concrete classification of individual DSSs within this framework is cumbersome.

In an earlier work, Alter [3] categorized DSSs with respect to the operations supported by the systems. In his taxonomy, Alter considers seven distinct types of DSSs that range between data-oriented to model-oriented systems in relation to the generic operations they perform. Figure 2.1 shows the distribution of the pro-

posed categories into data-oriented and model-oriented DSSs. The main operations supported by DSSs in these categories are:

- *File drawer systems*: provide access to up-to-date data items.
- *Data analysis systems*: manipulation of data; current or historical data files. They can either support domain-specific analysis tasks or general analysis tasks.
- *Analysis information systems*: provide management of information through the use of a series of decision-oriented data bases and small models.
- *Accounting models*: calculate the consequences of planned actions based on predefined estimators (accounting definitions).
- *Representational models*: estimate the consequences of actions based on models which are partially non-definitional (in contrast to accounting definitions). These models are oriented to describe possible connections between actions and outcomes.
- *Optimization models*: support the analysis of “best” possible outcomes based on the evaluation of a well-defined mathematical model and a series of constraints.
- *Suggestion models*: generate suggested actions based on the analysis of a set of well-structured rules or the evaluation of provided optimization methods.

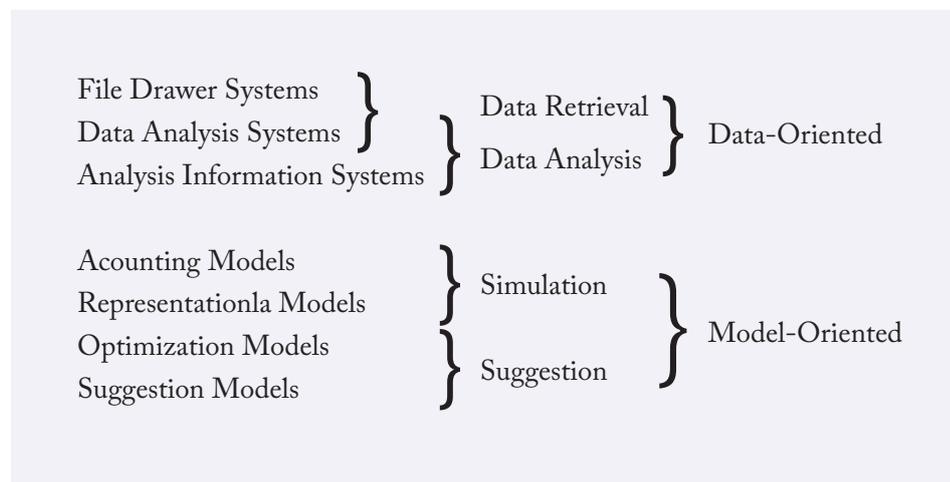


Fig. 2.1.: Alter’s decision support system types (adapted from [3]).

An extended and integrative approach was proposed by Power [80]. In his framework, two dimensions are used for the classification of DSSs. The primary dimension classifies DSSs into five categories that respond to the dominant technology component or driver of decision support: communications-driven, data-driven,

document-driven, knowledge-driven, and model-driven decision support systems. The secondary dimension classifies DSSs with respect to the targeted users, the specific purpose of the system, and the primary deployment or enabling technology. These categories are briefly described below.

Primary Dimension

- *Communications-driven*: focus on the integration of communication and collaboration decision support technologies to assist group decision making. The main difference between this type of DSS and the rest of DSSs' categories is the architecture of the system itself and the complementary tools used to support collaborative work.
- *Data-driven*: focus on the access and manipulation of large databases of structured data. The main operations supported by such DSSs refer to the query and retrieval of data that can be tailored to specific tasks.
- *Document-driven*: focus on the retrieval, analysis, and management of unstructured data sources such as text documents or web pages among others. For example, a search engine can be considered as a decision-aiding tool included in this type of DSSs.
- *Knowledge-driven*: analogous to Alter's suggestion models. This type of DSS incorporates reasoning systems (inference models) specialized to support a particular expertise. This expertise consists of knowledge about a particular domain, understanding of problems within the domain, and methods for solving these problems.
- *Model-driven*: focus on the access and manipulation of a model. Usually, this type of DSS suits a specific purpose, and therefore models' design and selection are consistently performed. The basic level of functionality provided by these type of DSS is the use of statistical and analytical tools.

Secondary Dimension

- *Targeted users*: different types of users have different roles for the interaction with a DSS. Power [80] distinguishes between inter-organizational and intra-organizational DSSs according to the type of access granted to the users of the system. Inter-organizational DSSs provide access to other systems as well as exclusive functionalities for the manipulation of the data. Intra-organizational DSSs are mostly designed as stand-alone applications for the internal use for individuals or groups within the same organization.

- *Purpose*: three sub-categories of DSSs are identified according to the purpose they serve: 1) function-specific: support specific functions or types of industry, 2) task-specific: support specific decision tasks in a specific industry, and 3) general-purpose: support a set of broader tasks that even includes the creation of more specific DSSs.
- *Deployment and enabling technology*: DSSs can be also classified with respect to the technologies used to implement and provide access to the decision support capabilities. For example, web-based technologies can be used as a front-end for any type of DSS. Likewise, stand-alone applications or client/server architectures can also be used as means to provide access to the decision support capabilities of any of the DSS types identified in the primary dimension.

Although DSSs are widely varying depending on the data they handle, the type of decision support, the application domains, users, and enabling technologies, these frameworks serve as a guide to position particular DSS developments and identify distinctive responsibilities and characteristics of a system. The next subsection is dedicated to studying the characteristics of simulation-based decision support systems, their applications in different domains, and the means used to communicate the outcome of such systems to the decision makers.

Simulation-Based Decision Support Systems (SB-DSS)

Consistently with the previous classifications of DSSs, Simulation-Based Decision Support Systems (SB-DSS) fall into the category of model-driven decision support systems. Model-driven decision support systems' dominant components are quantitative models, which are a simplified representation of a situation and its behavior. Ultimately, these models provide the functionality for the DSS. Some of the main characteristics of this type of DSS are [81]:

1. Data and parameters are provided by the experts or other knowledge source for the analysis of the situation.
2. Experts can manipulate the input parameters of these models to explore the impact they have in the generation of alternatives.
3. A user interface facilitates the access and manipulation of the model parameters to non-technical specialists.
4. The DSS is intended for its repetitive use in similar decision situations.

These quantitative models vary in nature, ranging from decision analysis models to optimization and mathematical models, multi-attribute and multi-criteria models, forecasting models, and simulation models among others. In the case of SB-DSS,

these quantitative models represent the characteristics and behavior of a real system. In principle, the typical workflow adopted by SB-DSS consists on the simulation of multiple scenarios for their later integrated analysis. Based on the analysis of alternative outcomes, experts can explore and assess the consequences of selecting a determined set of parameters and correspondingly plan the appropriate courses of action.

Common types of simulation models embedded in SB-DSSs include but are not limited to: probabilistic simulation, time dependent or discrete simulation, and visual simulation.

Certainly, a tool that facilitates the understanding of the outcomes of simulation models is visualization. This is one of the principles applied to visual simulation or interactive visual simulation.

Applications in Manufacturing

The use of simulation in the manufacturing domain has grown along with the increase in computational power over the last decades [97]. Moreover, there have also been significant efforts to make simulation models and packages available to a wider audience, which in turn has triggered more developments in this direction. In this subsection, the findings resulting from various surveys comprising related research from the last 50 years on the use of simulation in manufacturing applications are presented. The goal is to provide a picture of the progress of this applied research field and in the end, how visualization techniques are employed in this context for decision support.

In a set of surveys studying the evolution of DSS applications performed by Eom et al. [38, 40, 39], a clear change in the applications and tools embedded in DSSs in the last four decades is identified. In the third part of the survey that covers the period between 1995-2001, Eom et al. found out that a great portion of the applications of DSSs were oriented to assist decision making in the area of production and operations management (over 40%, the same as reported in the second part of the survey 1988-1994). Likewise, they identified an increase in the applications using artificial intelligence and visual interactive modeling.

Negahban and Smith [69] present an extended version of a previous survey [97] focusing on the use of simulation for manufacturing systems design and operation. The survey focuses on discrete event simulation applications in three particular cases: 1) manufacturing systems design, 2) manufacturing system operation, and 3) simulation language/package development for manufacturing systems applications. In the area of manufacturing systems design, there is a relatively large time frame for

decision making when compared to other areas, which require a quick reaction to an event. Here, simulation has been applied in four different sub-fields: general systems design and facility design, material handling system design, cellular manufacturing systems design, and flexible manufacturing systems design. In the case of manufacturing system operation, there is a short time frame for decision making. Usually, the systems are already in operation and simulation is used as a short-term planning aid. Typical applications involve operations planning and scheduling, maintenance operations planning and scheduling, real-time control, and operating policies. In terms of simulation language/package developments, two trends are identified by Smith: development of generic simulation models, general simulation modeling methods, frameworks, and software tools, and simulation metamodeling and optimization methods. These developments range from manufacturing simulators for process analysis or operational planning (among others) to the specialization of general programming approaches such as object-oriented programming to represent common structures in manufacturing systems.

The analysis of the literature reviewed this survey revealed clear trends with respect to research and development directions. For instance, there is a rapid growth trend in applications related to manufacturing system operation in the last two decades. Similarly, it indicates a slow but growing trend associated with manufacturing systems design applications, while applications in the area of simulation language/package development have slightly decreased within the same period of time. Although these surveys illustrate the direction of the research in SB-DSS, it is not clear how the results from these systems are conveyed to the decision makers. In particular, how visualization and its combination with other tools and techniques can help the understanding of SB-DSS outcomes.

A contribution towards the answer of this question was done by Mourtzis et al. [67]. The authors present a technique/tool-oriented survey on how simulation is used in product and production lifecycles. Among the techniques/tools highlighted in this survey, those involving the non-abstract representation of manufacturing-related components or processes are:

- *Augmented Reality (AR)*: used as means to provide decision makers with an enhanced environment by adding digitally generated information to a real world environment. The introduction of AR technologies in product design and manufacturing processes aims at improving product quality and reducing the costs of physical prototyping. Some examples are presented in [29, 42, 43].
- *Computer Aided Design (CAD)*: used to assist product design. Nowadays, many CAD systems integrate simulation models to support the early assessment of the performance of a new product.

- *Digital Mock Up (DMU)*: considers the 3D modeling of the mechanical structures of a system. This technique is often used to identify design problems without the need to produce a physical prototype. Multiple refinements are performed on the digital mock up until certain design and criteria are met. Commonly, DMU techniques are integrated within CAD systems [96, 109].
- *Virtual Reality (VR)*: concentrates on the use of specialized software and hardware to generate a simulation of an alternate real-like immersible scenario, which can be explored by the users. This technique has gained popularity in the field of manufacturing systems design as well as in process simulation. A very interesting application of this technique concerns collaborative decision support, where decision makers can share and explore a common virtual scenario [29, 66, 98].
- *Ergonomics simulation*: focuses on the understanding the interaction of humans with their environment. In the context of manufacturing systems, this relates to aspects of workplace ergonomics and how it affects the performance of the entire system. Simulation-based systems in this area allow the recreation of workplaces and tasks in an early stage of manufacturing systems design [59, 61].
- *Layout planning simulation*: in factory layout design, the use of digital representations of the allocations of machines and equipment in a shop-floor is imperative. Pre-designed 3D models of the machines and equipment are positioned within a virtual layout for its further analysis by combining it with other methods and techniques (e.g., AR, VR, ergonomics simulation, material flow simulation, etc.) [29].
- *Material flow simulation*: refers to the movement of material through a process or production routine. As expected, the factory layout as well as the production sequence have a great impact on the efficiency of this transit, and therefore in the throughput times. The simulation and optimization of these trajectories facilitate the flexible rearrangement of manufacturing facilities in accordance with changing production requirements.

Besides the technological challenges that arise from the emergence of new technologies, such as web-based platforms and cloud computing, there are also compelling challenges in regard to the representation of the outcomes from the simulation models and their further interpretation by decision makers. The before mentioned techniques and tools provide a great insight into the possible applications of visualization for simulation-based decision support.

Based on the findings from the presented surveys, one of the application areas which is growing back and that can greatly benefit from the use of visualization techniques to support decision making, is the design of manufacturing systems. Current developments in this area reveal the benefits providing proper visualization support (including 2D and 3D representations of the manufacturing system) in the communication of simulation results to groups of experts with different backgrounds as well as to non-expert audiences [98]. Even though novel and promising techniques have been lately introduced in SB-DSS for manufacturing, there are still open challenges regarding the ease of use of these systems and the way the simulation results are made available to decision makers [23, 81].

Applications in Building Performance Simulation

An application domain closely related to the design of manufacturing systems, from an architectural and ergonomics point of view, is Building Performance Simulation (BPS). Building performance simulation studies environmental conditions such as temperature, lighting, air flow, etc. within or around a building, which have a direct impact on the energetic and operational performance of a building and its occupants. As in SB-DSS for manufacturing, BPS serves as a decision support tool in the assessment of the configuration of a system (building) prior to its implementation (construction).

Countless software tools and plugins for CAD tools are available (e.g., Autodesk Revit [12], IES Virtual Environment [53], DesignBuilder [30], Open Studio [73], Diva for Rhino [100], Ladybug-Honeybee [93], VI Suite for Blender [103], etc.) that support partially or entirely the process of designing and evaluating a building design in terms of optimizing properties such as energetic efficiency, environmental impact, and human comfort among others.

BPS software commonly integrates different specialized simulation packages (e.g., CFD simulation, lighting simulation, energy costs simulation, etc.) within a single graphical user interface or sometimes in separated simulation modules for their configuration. As the design and evaluation of a building is mostly concerned about spatial aspects, one of the main techniques applied by BPS software for visualizing the simulation results consists of a 3D environment. Figure 2.2 shows an example of the visualization generated by DesignBuilder to illustrate the results of the air flow simulation inside a house.

The spatial context, implicit in building design, facilitates the use of several visualization techniques for the representation of simulation results. For example, color mapping, isosurfaces, isocontours, and texture based techniques are used for the representation of scalar values such as air temperature, humidity, wind speed, etc.

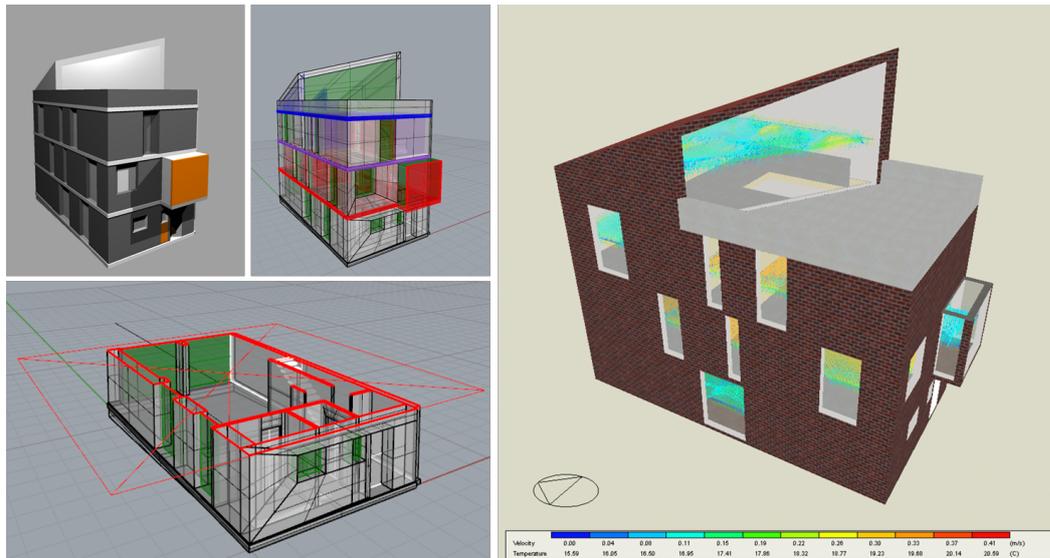


Fig. 2.2.: Visualization of air flow simulation results inside a house. Left: 3D model of the house created with Rhino. Right: visualization of the simulation results generated by DesignBuilder.

Likewise, vector glyphs and particle tracking are offered in some BPS software tools to visualize wind velocity vectors.

Interactive filtering techniques are also commonly offered by most BPS software tools. Multiple or single cutting planes and thresholding by values (applicable in combination with the techniques mentioned above) are used with the purpose to avoid visual clutter during the exploration and analysis of the local properties. In addition to these techniques, Haeb et al. [45] propose additional visualization techniques to improve the readability and interpretation, comparison and presentation of building design alternatives. For instance, multiple coordinated views, for the combination of abstract and non-abstract representations of the results; animation, for the visualization of time-dependent data; or feature-based techniques, to point out semantically interesting regions within the simulation results.

Although in the case of BPS, simulation results seem to be much easier to interpret given its implicit spatial context, BPS systems still experience low acceptance from users due to usability issues as reported in [10]. Another obstacle encountered by decision makers is that because of the diversity of backgrounds, not all of them are necessarily trained to read and interpret the available data representations. Hence, a domain-sensitive approach using background knowledge from the different involved disciplines should be adopted in the design of visual representations of the simulation results.

2.2 Contributions from Research in Visualization to DSS and SB-DSS

Visual Analytics

Visual analytics is defined as the science of analytical reasoning supported by the combination of automatic data analysis techniques and interactive visualization into a unified system. Visual analytics applications are not exclusively dedicated to decision support but they also facilitate the understanding of complex phenomena.

There have been some examples in the application of visual analytics to the analysis of data simulated or produced in manufacturing systems. For instance, Wörner and Ertl [122] present a visual analytics system to support real time process planning. Timeline views and table views are used to visualize the state of the machines and work pieces respectively. A spatial view helps to relate the different steps of the process within the physical layout of the factory. The visualization techniques used in this system include 2D and 3D visualizations, in conjunction with multiple coordinated views that incorporate brushing and linking capabilities.

Xu et al. [124] designed a visual analytics system to evaluate the performance of an assembly line using either historical or real-time data. The main goal of this work was to enable experts to interactively detect anomalies in the assembly process and consequently support decision making and planning of actions. Similar to the previous example, the strategy to visualize multiple aspects of the analyzed environment is the use of coordinated views along with the display of details-on-demand. A timeline view inspired by Marey's graph [111] is used to visualize the machining progress of single or series of workpieces. The tool implements aggregation and classification methods to simplify the visualization of normal assembly cycles while highlighting outliers. Additional coordinated views are intended to depict spatial information (e.g., physical configuration of the workstation within the assembly line), historical information (calendar view), or anomalies information (fault codes panel).

Sorger et al. [102] introduce LiteVis, a system for the analysis of lighting simulations in an office environment. The system offers two coordinated views, the simulation view showing the illuminance distribution using false color maps superimposed on a 3D model of the simulated area, and a ranking view that uses custom metrics for the classification of different lighting alternatives. A use case demonstrating the applicability of LiteVis in a real-world context was conducted. The feedback obtained from lighting designers indicated that the system helped in achieving more efficiency and certain evaluations of lighting alternatives.

Jo et al. [56] developed an interactive Gantt diagram based system for the interactive exploration and scheduling of production tasks. A case study using data from a semiconductors manufacturing facility in Korea was conducted to evaluate the capabilities of the system. The system, named LiveGantt, consists of three graphical user interface components: a main window, exploration history view, and the visualization controller. Within the main window, there is a schedule view that provides an overview of the entire schedule; a performance view, for the detailed monitoring of a schedule over time; a resource view, to explore the utilization of resources; and a package view, which provides information about the completed packages over time. The results of the case study demonstrated that the visualization and interaction techniques offered by the system facilitated the detection of deficiencies and their later correction. However, the systems does not count with techniques that support comparison of multiple schedules.

These examples show the potential of visualization support for decision making with respect to the analysis of large and complex sets of simulations or other types of data. The combination of abstract and non-abstract representations of the data and their exploration through multiple coordinated views also pointed out a positive impact on the users of these systems in generating insights about their data.

2.3 Challenges for Visualization Support in SB-DSS

Heilala and Maantila [47] identified three major challenges for the design and development of SB-DSSs in the area of manufacturing: 1) data integration, 2) automated simulation model creation and updates, and 3) visualization of results for interactive and efficient decision making. Concerning the third challenge, the authors argue that the use of simulation with intuitive graphical user interfaces and visual representations of simulation results serves as a useful resource for the evaluation of scenarios even for decision makers who are not familiar with simulation technologies. Punctual aspects related to this challenge refer to:

- Support for the identification of relevant pieces of information within the simulation results.
- Use of visual representations that consider specific-domain knowledge to speed up the apprehension process.
- Intuitive and interactive user interfaces for the exploration and analysis of simulation results.

Rohrer [90] highlights the importance of visualization in manufacturing simulation. He emphasizes on the use of interactive animations for the presentation of simulation results to decision makers. Regardless of the means advocated by Rohrer, complementary aspects (mostly oriented towards interaction capabilities) that make part of the challenges include: interactivity, realism, performance, flexibility, and ease of use.

- **Interactivity:** integration of mechanisms for the progressive interactive exploration of elements within the model (details-on-demand) through contextual menus and coordinated views.
- **Realism:** in the case of non-abstract visualizations, realism helps ensuring model credibility and encourages the immersion of decision makers in the process.
- **Performance:** guarantee high quality visualizations and smooth interaction to prevent disruptions during a decision making process.
- **Flexibility:** possibility to easily control the visualization (e.g., add or remove elements to focus on particular characteristics of the model or the simulation results).
- **Ease of use:** ease of integration of new visualization techniques to the system in order to support new tasks.

In addition to these challenges for visualization support in SB-DSS, Zhu et al. [127] also point out a challenge in establishing criteria and protocols for the evaluation of visualization systems. An effective approach to tackle all these challenges is the integration of User-Centered Design techniques into the design of interactive visualizations for decision support. The following section explores some of this techniques and their application.

2.4 Approaches for Visualization Support in SB-DSS

This section is a compilation of User-Centered Design (UCD) techniques and a methodological approach to the design of interactive visualization to support decision making. UCD techniques have proven to be a successful approach to overcome the challenges previously described.

User-Centered Design Methodology

User-Centered Design (UCD) methodologies have been widely used to guide the development of visualization systems in diverse application domains [7, 8, 19, 47, 62]. UCD approaches provide designers with a structured way of developing products that suit user needs. The main principles comprised in this view are: an early focus on understanding the user and the context of use, empirical testing and evaluation of the product design by representative users, and an iterative design process of four stages [79]. The goal is to make products more usable, in other words, “The product should suit the user, rather than making the user suit the product” [27].

A large number of visualization projects that use UCD approaches are based on the definition of ISO 13407:1999 [54]. This standard called “Human-Centred Processes for Interactive Systems” provides general guidelines for introducing a UCD approach within a project. It describes an iterative process that involves at least four iterative stages before getting into the final design. According to this standard, the employment of UCD processes has several benefits for products and users: products become easier to understand and use, products can improve user satisfaction, users can increase their productivity, and product quality is enhanced.

Wassink et al. [119] propose a three phase process for the design of interactive visualizations. These phases are: early envisioning phase, global specification phase, and detailed specification phase. Each phase can contain more than one iteration and each iteration consists of three activities: analysis, design, and evaluation where the authors suggest some methods to guide the design process.

Fernandez et al. [41] proposed UCIV 4 Planning, a methodological approach to support the design of interactive visualization for urban and regional planning inspired by Wassink et al.’s work. Although this approach focuses on the domain of urban and regional planning, the overall process structure and UCD techniques can be easily generalized for their use in other application domains.

Analogously to Wassink et al.’s approach, UCIV 4 Planning consists of three-phases which involve a set of activities that help to collect relevant information about decision makers and their analysis task. This information is later used to make suggestions of possible visualization and interaction techniques that can be applied in SB-DSSs.

UCIV 4 Planning’s core is the detailed description of decision makers’ analysis tasks. This includes a description of a guiding question (what do decision makers need to know about the data?), the data that is required to answer the guiding question, and which decision makers of other domains have an influence on the answer to this guiding question.

Figure 2.3 illustrates the general concept of the UCIV 4 Planning approach. It is a cyclic development model consisting of three phases: analysis, design, and implementation. Each phase uses the knowledge-base of the involved decision makers and is guided by analysis tasks. The results of each phase are assessed through a feedback activity that determines if it is necessary to repeat the phase or if we can proceed with the next phase. Below, an outline of the phases and their activities is presented.

Phase 1: Analysis

The goal of phase 1 is to learn about the decision makers and the context of use of the visualizations. The outcome of this phase is a rough analysis tasks inventory.

- Activity 1: consists of three sub-activities: 1) decision makers' profiling, 2) description of the context of use for the interactive visualizations, 3) definition analysis tasks. Questionnaires, observations of decision making session, and unstructured interviews are the techniques used to build the first picture of the decision making context.
- Activity 2: classification of analysis tasks. A classification method that enables the inference of visualization and interaction recommendations. This classification method consists of three parts: definition of analysis task types relevant to the application domain (e.g., determining trends in a dataset, comparison of attributes, etc.), identification of required visual operations based on Wehrend and Lewis taxonomy [120], and identification of required interaction operations based on Yi et al. 's taxonomy [125].
- Feedback activity: focus group session [83]. This session is conducted with the purpose of sharing and validating the results of the two previous activities with the decision makers.

Phase 2: Design

Phase 2 examines the criteria for selecting visual representations and interaction techniques according to the analysis task types. The outcome of this phase is a set of low/high-fidelity prototypes evaluated by decision makers with respect to the suitability of the selected visualization and interaction guidelines.

- Activity 1: literature review regarding decision makers knowledge-base and visualization conventions as well as human perception design guidelines [118].
- Activity 2: prototyping. Low-fidelity prototypes such as sketches or paper prototypes [99] can be used for presenting possible visual representations and modeling interactions. Hi-fidelity prototypes (e.g., simple interactive programs produced using Processing [87]) can be used to demonstrate some of the visualization and interaction aspects planned for the final implementation.

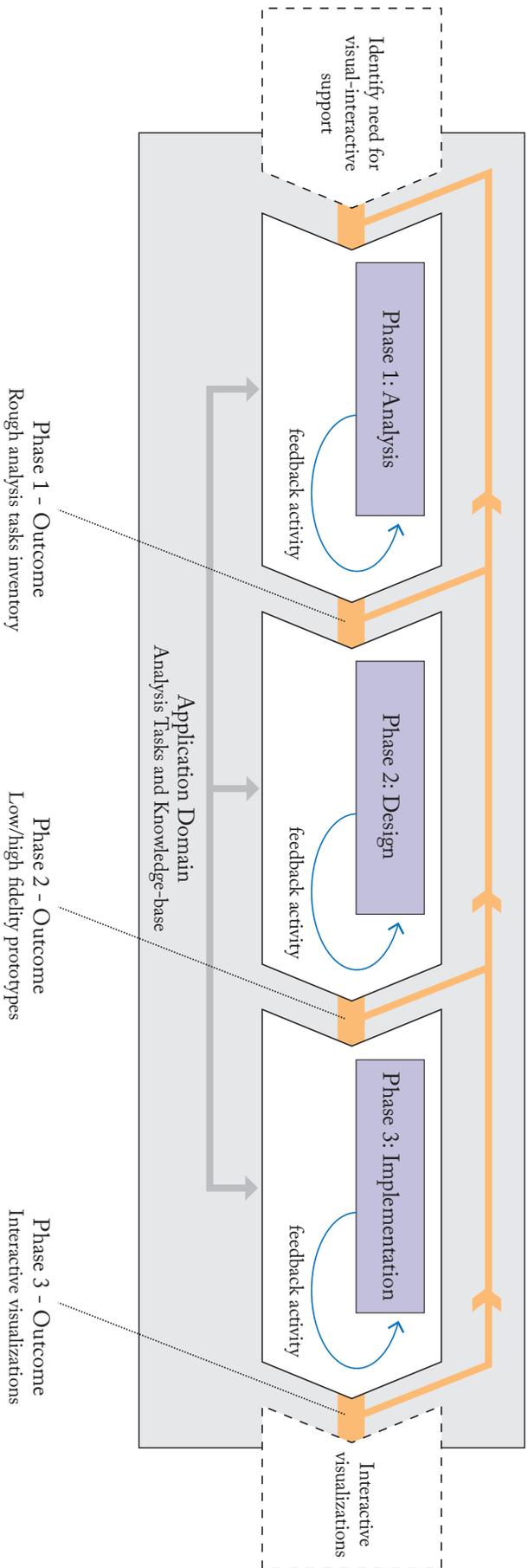


Fig. 2.3.: UCIV 4 Planning approach (adapted from [41]).

- Feedback activity: Participatory Design (PD) session using paper prototyping [74]. Low/high fidelity prototypes are presented to the decision makers for their early evaluation.

Phase 3: Implementation

Phase 3 incorporates the selected visual representations and interaction techniques into fully functional interactive visualizations. The output of this activity is a set of interactive visualizations assessed with the decision makers through usability tests or expert evaluations.

- Activity 1: analysis of the results of the PD session.
- Activity 2: final selection of techniques and implementation. Definition of technologies for the implementation of the interactive visualizations.
- Feedback activity: usability test or expert evaluation. Three usability criteria are considered in the evaluation of the produced interactive visualizations: 1) effectiveness, 2) efficiency, and 3) satisfaction [112].

Analysis of Lighting Simulation in Factory Planning

Lighting in industrial facilities is a critical aspect considering the numerous hazards that derive from an inappropriately illuminated environment. For example, excessive or insufficient brightness at workstations can cause visual fatigue or headaches among other symptoms. In consequence, accidents associated with the proper identification of the position, shape or motion of objects are more likely to occur. This, in turn, has a direct impact on the quality and productivity of the entire factory. Although more factors than purely lighting affect the ability to perform a visual task effectively and efficiently, lighting design and analysis plays a key role and can be addressed in the early planning stages. Although several lighting models and software tools have been developed to assist lighting design in various environments, none of them directly supports the analysis and comparison of multiple alternatives from a spatial and ergonomics perspective.

This chapter introduces *viPhos*, a simulation-based decision support system that I developed with the purpose of assisting the process of lighting design in factory planning. It assists factory planners in the evaluation of lighting alternatives to select the best fitting configuration concerning the compliance with a determined standard. *viPhos* combines simulation, analysis, and visualization tools and techniques that facilitate the global and local (overall factory or workstation / functional units, respectively) interactive exploration and comparison of lighting alternatives. The following subsections present the context of use of the system as well as implementation details and case studies in factory planning and road construction work zones.

3.1 The Factory Planning Process

The close connection between planning the production and the building of a factory requires the interaction of multiple aspects. Traditionally, these aspects have been addressed separately, but more recently there is a growing interest in reaching a seamless integration to allow experts to see the entire planning process as a whole. With this in mind, the concept of “synergetic factory planning” emerged [121]. This concept integrates into a single framework the steps considered in the production planning process and the building design process. Thus, the exchange of information between these two processes favors a more informed and efficient decision making.

Synergetic factory planning merges through common milestones, the outcomes of the production planning process and the building planning process. Six stages are defined in this factory planning approach. From the setting of objectives and base analysis to the ramp-up support after the implementation of the plan. Figure 3.1 illustrates the planning stages comprised in this approach.

Following, the results available at each milestone of the synergetic factory planning process are presented as described by Wiendahl et al. [121].

- M1: Factory mission and vision, coordinated requirement profile, factory strategies, targets and fields of action, building specifications in accordance with regulations, procurement and distribution model, spatial attributes of required machinery, and approximate project schedule.
- M2: Building volume and spatial schedule (rough layout of the factory), estimate of costs, integrated 3D spatial and production concept, and updated project schedule.
- M3: Detailed layout with operating facilities positioned precisely, approval from prospective users, approval from authorities, execution plan for contractors, ensuring the plan's feasibility and cost compliance, cost calculations, room list, and detailed project schedule.
- M4: Invitations for bids from potential contractors, cost estimates, and detailed project schedule.
- M5: Performance tests and approvals of facilities and buildings, costs statements in accordance with regulations, and final documentation.
- M6: Determination of the full load capacity, evaluation of the target attainment, and transfer of documentation and balancing accounts.

Due to its interdisciplinary and integrative nature, the synergetic factory planning approach also encourages the use of new methods to support the planning process, in particular, digital methods such as 3D modeling and simulation. Digital methods help to articulate all the stages of the synergetic factory planning process since these representations can be easily modified, updated, and refined as the process evolves.

Two complementary concepts closely related to this idea are the “Digital Factory (DF)”, defined in the guideline VDI 4499 Part 1-2015 [116], and the “Building Information Model (BIM)”, conceived in the architecture domain [13]. While DF refers to a network of digital models, methods, and tools within a holistically integrated data management system as a support for the various phases of the planning process, BIM, defines the technical basis for the exchange of the digital data of a building. This demonstrates the increasing effort on standardizing the use of digital methods in the factory planning process and the need for systems that support this approach.

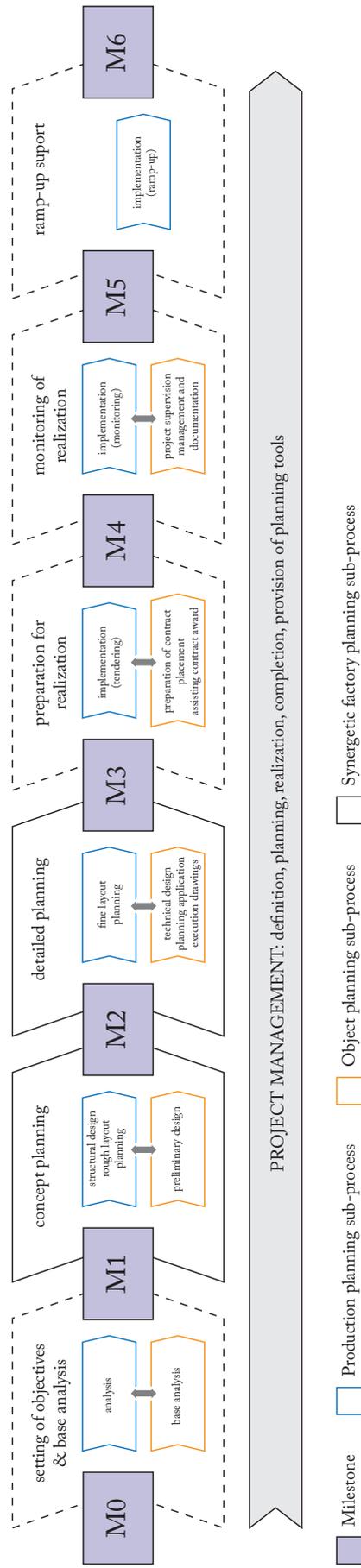


Fig. 3.1.1.: Stages of the synergetic factory planning approach. Adapted from [121]. Concept planning and detailed planning stages are highlighted to indicate the potential application of 3D modeling and simulation methods during these stages.

The stages of the synergetic factory planning process where digital methods, in particular simulation, become essential are the concept planning stage, and later the detailed planning stage. During the concept planning stage, structural or functional units are defined and distributed within the building floor area complying a specific order that favors, for example, the material flow and transportation of finished products. 2D and 3D models illustrate the planned distribution of the functional units and provide a first overview of architectonic details (results of milestone M2). During the detailed planning stage, the exact position and dimensions of machinery, equipment, and furniture is integrated into the plan. Energy supply connections, as well as ventilation and lighting installations, are also considered at this stage (results of milestone M3). Regarding the development of digital methods and tools that support these stages two trends can be highlighted: 1) simulation tools to tackle the so-called “facility layout problem” [35] and 2) physical simulation tools to study environmental conditions such as indoor climate conditions, energy performance, or natural and electric lighting among other aspects [11].

In this context, simulation plays an important role since it supports the alignment and refinement of both rough factory layout and fine factory layout. For instance, the fine layout of a factory, besides considering the optimal material flow should also consider human factors for the cases of not fully automated facilities. Here, simulation is a tool that facilitates the evaluation of particular spatial arrangements with respect to production and human factors’ requirements. A clear example of this can be the simulation of lighting conditions inside a factory. As diverse processes and tasks take place in different locations in a factory, lighting requirements vary accordingly. The modeling of different lighting alternatives and their corresponding analysis bring immediate feedback to the experts regarding the lighting distribution in all areas prior to the implementation of the plan.

3.2 Simulation-Based Lighting Design for Factories

An important aspect considered while designing a lighting solution for a factory is related to workers’ performance and comfort within the environment. From the ergonomics perspective, one of the main questions is: what is a good lighting environment?. Several experiments that study the impact of different lighting conditions in human performance and comfort have tried to find a clearer answer to this question. For instance, Pellegrino [76] conducted an experiment to quantitatively and qualitatively compare three lighting systems in an office environment using well-known metrics such as illuminance, luminance, glare indices, as well as questionnaires registering participant’s perception of performance, satisfaction, and comfort. This study did not find a significant correlation between the physical measurements and

the qualitative assessment collected by the questionnaires, revealing the subjective nature of the quality of lighting. More recent studies [4, 16, 57, 75] consider the physiological and psychological effects of illumination and color temperature of the lighting source on human responses. One conclusion from all these studies is that the evaluation of the quality of lighting, in any environment, is highly subjective. These and other studies, however, have helped in the identification of minimum lighting requirements for different environments. This has led to establishment of the existing lighting standards such as the European standard EN 12464-1 [26] and AS/NZ 1680.1:2006 [107] among others.

These standards provide a base line for the design of new lighting systems in correspondence with the type of task to be performed by humans. The reference values refer to illuminance, illuminance uniformity, luminance ratios, and glare indices among other parameters. Despite all the existing studies and standards, it is still very difficult to establish the criteria and parameters that define a “good lighting environment”. Therefore, an approach that integrates and combines the assessment of multiple quality metrics with visualization techniques is favorable in developing a simulation-based decision support system.

3.3 Research Goals and My Contribution

The goal of this project is the development of a tool that assists lighting designers and factory planners in the analysis, exploration, and evaluation of electric lighting simulations. This research contributes to the enhancement of visualization support for SB-DSS by providing an interactive visualization and analysis environment for the exploration and comparison of multiple lighting designs and their compliance with various standards and requirements.

viPhos combines modeling, simulation, analysis, and visualization techniques to support lighting design tasks. From the modeling and simulation point of view, the system integrates multi-resolution simulation grids to allow experts to perform a finer exploration of the light distribution and evaluated metrics on priority regions of the scenario. From the analysis point of view, the system supports the evaluation of standard metrics along with custom defined metrics (e.g., feature-based metrics) oriented to support the validation of compliance with lighting standards and the comparison among alternatives. From the visualization point of view, the system provides common interaction and visualization techniques as multiple coordinated views for the local and global exploration of raw simulation results as well as the outcomes of the evaluated metrics.

In contrast to existing lighting simulation tools, the visualization and analysis support that I incorporated in *viPhos* facilitates the comparison of lighting design alternatives

within the spatial context of the simulated scenario. Recent research has also been done towards the enhancement of the comparison capabilities of commercial lighting design tools [102], however the focus remains on the classification and ranking of lighting alternatives based on the evaluation of standard metrics rather than their spatial contextualization within the simulated scenario.

3.4 The *viPhos* SB-DSS

3.4.1 Overview

viPhos is a Simulation-Based Decision Support System that assists the design, analysis and evaluation of lighting design alternatives. In contrast to similar tools, it facilitates the analysis and interpretation of lighting simulation results by offering the following features:

- Integration of open source tools for modeling, simulation, analysis, and visualization of lighting designs. *viPhos* uses a powerful set of tools and packages (Blender, VI-SUITE, RADIANCE, and VTK) to support the entire process of designing and evaluating lighting alternatives.
- Automated comparison at global and local level of lighting alternatives against standards based on common and expert-defined metrics. Statistical techniques from the image processing domain are applied to highlight areas that require a redesign or revision.
- Interactive visual exploration of simulation results. Three main views provide access to different analysis approaches of the simulation results, from the exploration of raw results to the evaluation of the defined metrics and summarization of results. Multiple coordinated views simplify the identification of relationships between the spatial (bound to the physical layout) and numerical (detailed quantitative values) attributes of the simulation results.

The introduction of *viPhos* within the synergetic factory planning process will enable experts to gain a better understanding of the effects of lighting configurations to favor workers' performance and comfort for different types of visual tasks. *viPhos* can also be adapted for studying other lighting environments like outdoor night work, which is common in road construction projects.

3.4.2 Related Work

For over three decades, a great effort has been dedicated to the development of computational models that describe as accurate as possible the complex behavior

of light and its interaction with the environment. Although these models are ever more accessible to a larger audience, their actual integration into the building design process is still challenging. Two of the main obstacles for this integration is the ease-of-use of these models and the ability to interpret simulation results effectively [25, 49]. To tackle the ease-of use obstacle, several software packages in the architecture industry have incorporated these models within CAD tools like Ecotect, ElumTools for Autodesk Revit, Diva for Rhino, and 3DS Max among others. Likewise, specific lighting simulation software packages (e.g., Agi32, ADELINe, DIALux, Relux, Lightscape, etc.) have been developed with the purpose of providing a user-friendly interface for the utilization of these models. Although they are not particularly designed to model lighting conditions within a factory, they support the high-level validation of lighting conditions against several standards that consider different activities in industrial environments.

Roy [92] and Ochoa et al. [71] provide a comprehensive survey of lighting simulation tools in building science. Although they do not focus on industrial environments, they point out different lighting models used in different simulation packages, such as raytracing and radiosity models, stand out for their computational efficiency and accuracy.

As natural light is being reincorporated as an important aspect in industrial facilities (in contrast to the windowless factory designs from 1970's), a great portion of the recent studies using lighting simulation are focused on daylight instead of electric lighting. However, simulation of electric lighting still plays an important role in the design of energy efficient lighting environments. Consequently, several studies [48, 65, 94, 101] evaluate the performance of different simulation tools/packages for electric lighting. Among the systems developed, the most popular, freeware tools include: RADIANCE [117], DIALux evo [31], and ReluxDesktop [88]. Some of the strengths and weaknesses of these simulation tools are presented in Table 3.1.

In evaluating visualization and simulation-based analysis of lighting alternatives, Sun et al. [110] studied the energy consumption of fluorescent and LED luminaires that are commonly used in households. To this end, the authors simulated and compared photorealistic renders (generated using DIALux) and illuminance calculations (generated using LightTools), plus the estimation of energy consumption for each alternative. The comparative analysis was done by side-by-side observation of the images resulting from the simulation. Although this strategy works for comparing small simulation sets, it does not scale very well for cases where multiple simulation runs and analyses need to be performed. For these cases, the usage of an interactive visualization tool that dynamically adapts to the characteristics of the data sets is more suitable.

	Strenghts	Weaknesses
RADIANCE	<ol style="list-style-type: none"> 1. Free and open source lighting simulation engine. 2. State of the art lighting simulation engine that can be coupled with custom-made user interfaces. 3. Backwards raytracing method. 	<ol style="list-style-type: none"> 1. Not user-friendly for non-experienced programmers. 2. Middleware software is required to have access to an easy-to-use interface (e.g., VI Suite).
DIALux evo	<ol style="list-style-type: none"> 1. Free lighting design software with a friendly user interface. 2. Simulation complying with most used international standards (e.g., EN 12464). 3. Supports data exchange with common CAD software. 4. Luminaire database available within the software tool. 5. Interactive customization of light attributes (e.g., light intensity). 	<ol style="list-style-type: none"> 1. The tool does not directly support simulation-based comparison of lighting designs. 2. Despite the complete user interface, there are too many parameters to configure. 3. Export of results for further analysis with other tools and techniques is limited.
RELux Desktop	<ol style="list-style-type: none"> 1. Free lighting design software with a friendly user interface. 2. Simulation complying with most used international standards (e.g., EN 12464). 3. Compatibility with Autodesk Revit. 4. Integration for energy consumption and cost-efficiency analysis of luminaires. 5. Luminaire database available within the software tool. 	<ol style="list-style-type: none"> 1. Not well documented. 2. The tool does not directly support simulation-based comparison of lighting designs. 3. Export of results for further analysis with other tools and techniques is limited.

Tab. 3.1.: Strengths and weaknesses of three free lighting simulation tools/packages.

In this direction, several researchers have discussed about visualization support for the analysis and interpretation of lighting simulation results. For instance, Roy [92] does not only discuss the computational methods used in four simulation packages (ADELINE, Lightscape, Microstation, and RadioRay) but also comments on the alternatives offered by these tools to present the simulation results. Also analyzed by Ashmore and Richens [9], these alternatives respond to the need of designers to interpret photometric data in a graphic way. Some of the visualization techniques listed by these two studies include: isocontours, false-color surfaces, and photorealistic rendering. Ochoa et al. [70] provide a detailed review on the state of the art of lighting simulation in building design. They classify the output provided by simulation tools in two categories: quantitative and qualitative output. The quantitative output consists basically of text-only files that contain photometric data (e.g., illuminance, luminance, glare, etc.). The qualitative output is expressed as different types of image output that depict a mapping from the quantitative output to a graphic representation. Iversen et al. [55] compare nine lighting simulation packages in the context of daylighting simulation. Despite the analysis focuses on the accuracy of daylight computation for each tool, it also presents the alternatives

for the graphical representation of daylight factor levels. Once again, isocontours and false-color maps along with tabular data are the preferred techniques by most of the tools for making the simulation results available to lighting designers. Similar studies comparing other tools can be found in [94, 114].

Although not in the lighting simulation domain but in the building performance simulation domain, Prazeres and Clarke [82] address the communication of simulation output to the users. Considering the fact that in most cases simulation output is heterogeneous with respect to the data type, a reasonable approach is to offer specialized visualizations according to the type of data that needs to be displayed. The authors of this paper present a survey of visualization techniques that can be used in the context of the visualization of building simulation results. Among these, interactive 3D visualizations and virtual reality environments are highlighted as they allow the exploration of the results from different points of view. Srivastav et al. [106] argue that even when visualization techniques have been successfully applied to the design and presentation of building designs, in the field of building simulation, there is still a gap in the application of these techniques at the service of more complex analytical tasks (e.g., analysis of multivariate data). Therefore, approaches from domains like scientific visualization should be considered and properly adapted in the context of building or lighting simulation. Haeb et al. [45] discuss this issue by performing a simple study comparing the visualization capabilities of two simulation tools (IESVE and DesignBuilder, also capable of computing simple lighting simulations). Here, the authors identify visualization techniques used in other application domains that could be used for the visualization and analysis of indoor environment simulations (mostly thermal conditions). This study is analogous to the intention of our study since it highlights additional visualization and analysis techniques that can potentially enhance the interpretation of simulation results.

In order to gain a better understanding about these techniques in the field of lighting design and how they are presented to the decision makers, a comparative evaluation of the visualization and interaction capabilities of DIALux evo [31] and ReluxDesktop [88] for supporting the spatial-based analysis and exploration of simulation results (RADIANCE was excluded of this evaluation since it does not have a graphical user interface of its own) was performed. Table 3.2 presents a summary of the available techniques for the presentation of simulation results in both tools.

3.4.3 Analysis Workflow

Simulation-assisted lighting design should be seen as an iterative process where a lighting solution is iteratively modified until certain quality criteria is met. Founded on the documentation in [68, 128], the steps comprised in a typical simulation-assisted lighting design process is proposed as part of the *viPhos* system:

	DIALux evo	RELux Desktop
Photorealistic renders	Available for the display of luminance distribution (correlated color temperature is also observable through this view).	Available for the display of luminance distribution (correlated color temperature is also observable through this view).
Isocontours	Available for the display of illuminance distribution on the calculation objects (e.g., working plane or visual task area).	Available for the display of luminance and illuminance distribution on the calculation objects (e.g., working plane or visual task area).
False-color maps	Available as 2D maps for the display of illuminance values on the calculation objects.	Available as 2D maps for the display of illuminance values on the calculation objects.
	Available as 3D maps depicting the illuminance distribution on all surfaces within the room.	Available as 3D maps depicting the illuminance distribution on the main surfaces of the room (walls, ceiling, and floor).
Value charts	Available for the display of illuminance values. The spatial context is preserved via wireframe view of the room.	Available for the display of luminance and illuminance values. The spatial context is provided via plane axes indicating the dimension of the room.
2D plots	Available as radial plot displaying the UGR for each angle within the viewing angle range. Accessible only through the report generation tool.	Available as radial plot or Cartesian plot displaying the UGR for each angle within the viewing angle range. Additional information about the position, orientation, and viewing angle of the observer can be accessed through complementary views.
Summary reports	Available. Reports are automatically generated including a summary of all calculated metrics for the whole room and all calculation objects. Reports can be later exported as a pdf file. Compliance with lighting standards is only indicated in these reports but it is not integrated into any of the other visualizations.	
Combined views	Available. Isocontours, false-color maps and value charts displaying illuminance distribution can be combined into a single visualization.	Not available.
Visual comparison of alternatives	Not available. The only option to compare lighting alternatives in both tools is oriented to the energy efficiency of the selected luminaire. It is possible to compare the costs and energy consumption for multiple luminaires but the option to compare simulation results for two or more different lighting solutions is not available.	

Tab. 3.2.: Summary of techniques in DIALux evo / ReluxDesktop for the presentation of simulation results.

1. *Identify lighting requirements.* Based on the fine factory layout resulting from the detailed planning stage (see section 3.1), this step includes the analysis of the physical space to be illuminated and the extraction of lighting requirements in accordance with the type of task to be performed in each functional unit of the factory.

2. *Select lighting equipment.* The selection of luminaires and control equipment is done in regard to the requirements identified in the previous step. The technical specifications of the selected luminaires are commonly provided by the manufacturers as photometric data files.
3. *Model the physical space.* The 3D model created to illustrate the fine layout of the factory is refined to integrate relevant information for the simulation. This model must depict the spatial distribution of objects (e.g., furniture, openings, machines, etc.), the optical properties of all surfaces within the model (materials definition), the subdivision of the space according to visual task types, and the proposed arrangement of luminaires.
4. *Setup and run simulation.* This step requires the definition of input data and calculation objects. The input data consists of the 3D model and photometric files of the selected luminaires. The calculation objects consist of a set of geometric elements that serve as “sensors” for the computation and storage of simulation results. Relevant aspects for the configuration of these objects are their position and resolution (when a calculation object - plane - is defined).
5. *Analyze the results.* The impact of a particular design is analyzed in terms of performance, comfort, and safety. This analysis can lead to modification in the original design, and therefore a new design and simulation cycle must be performed.

Typical simulation-assisted lighting design processes require conducting multiple simulation cycles and thus, the task of comparing alternatives is crucial to find an optimal solution. The goal of this task is to determine, among a collection of simulations, which one fulfills more appropriately a set of requirements. To this end, the European standard EN 12464-1 “Lighting of work places – Indoor work places” [26] is used as reference. According to this standard, any lighting design must satisfy three basic human needs: 1) visual comfort, referring to the perception well-being of workers; 2) visual performance, the lighting favors the satisfactory performance of visual tasks; and 3) safety, no accidents should be related to deficiencies in the lighting environment.

3.4.4 Visualization and Interaction Requirements

The visualization techniques currently included in most lighting simulation software are ideal to facilitate the global understanding of the lighting conditions for a designed environment. Based on the review of related work and the comparison the two lighting simulation software packages tested (DIALux evo and ReluxDesktop), and the results of conducted unstructured interviews to an architect and a lighting

expert, the requirements for the visualization support in lighting simulation analysis were extracted.

- [R1] *Preserve spatial context for the analysis of simulation results*: since most data generated by lighting simulations depend on the physical properties of the objects in a building or room, there must be a clear representation of the spatial distribution of light within the simulated environment.
- [R2] *Enable multilevel exploration of simulation results*: the system should enable the global (overall factory) and local (per functional unit or workstation) exploration and analysis of the simulation results.
- [R3] *Highlighting of critical regions that do not fulfill the requirements*: the analysis and visualization techniques must favor the identification of regions within the simulated environment that have undesirable behaviors (e.g., too bright or too dark regions).
- [R4] *Use of multiple coordinated views showing alternative data representations*: by offering multiple synchronized views with different representations of the data, experts can identify interesting behaviors and find relations between different data dimensions.
- [R5] *Facilitate the visual comparison of alternatives*: incorporate explicit visual strategies for the comparison of different subsets of the data. This also includes the capability to generate and compare visual summaries of large sets of simulations with similar input parameters.
- [R6] *Use of visual idioms known in the application domain*: this not only contributes to the learnability (also known as the usability of the system over time), but also to the acceptability of the system among experts.

An additional non-functional requirement was expressed concerning the possibility to freely extend and adapt the system to support new tasks. Moreover, the reuse of existing tools and packages can reduce considerably the development time.

- [R7] *Integration of freeware / open source tools and packages for the development of the system*: this requirement appeals to the reuse of successful and validated blocks of code (such as geometric modeling tools, lighting simulation engines, or visualization libraries among others) that can be later extended in line with specific-purpose needs.

3.4.5 Implementation

Two principles drive the design of *viPhos*: use of open source tools and libraries; and maintainability. These two principles allow further development and research with the system and facilitate supporting new requirements or updates. To achieve these two principles the “Separation of Concerns (SoC)” software design principle [33] was applied by dividing the system into three modules each with a separate responsibility. Figure 3.2 depicts these three modules and their inter-connections. The modules are: Simulation Engine, the Analysis Engine, and the Visual Exploration Interface. Although “data input” is not explicitly declared as a module, it is included as part of the process pipeline. While inputs **a** and **b** are directly used by the simulation engine, input **c** is only used later on in the analysis engine (see Figure 3.2). The system is designed such that it would allow to move directly from simulation to visualization without any analysis.

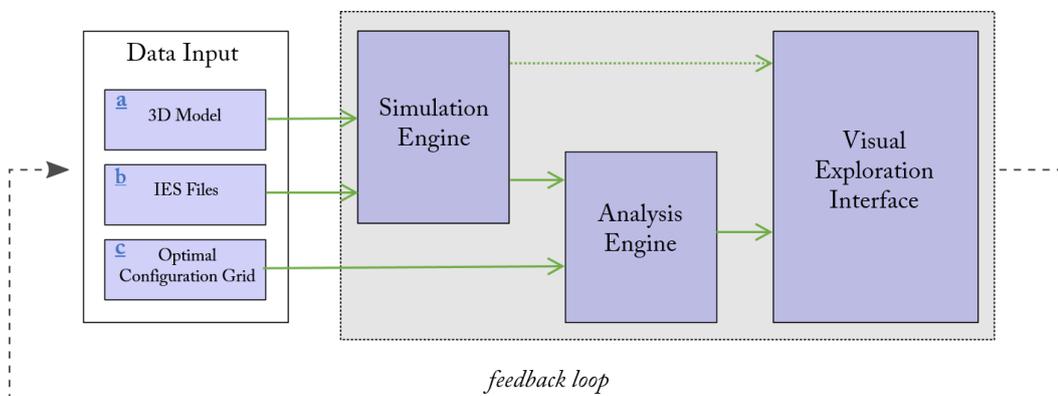


Fig. 3.2.: Architecture and analysis workflow of lighting simulations implemented in *viPhos*

Input Data

The preparation of inputs **a** and **c** is carried out by using a third party 3D modeling software, in our case Blender [15], a free and open source 3D modeling software. Input **b** contains the photometric data of the luminaires and it is usually provided directly by the manufacturers. A detailed description of the inputs required for this module is provided below.

- a) *3D model(s) of the factory layout.* This model describes the physical characteristics of the planned facility. It includes: 1) the position and orientation of the equipment, 2) the description of the optical properties of all surfaces within the model, 3) the position and orientation of the luminaires, and 4) an additional geometric element, the calculation object where the illuminance values will be stored after the simulation is executed. If the calculation object is a plane,

the height of this plane in the 3D model determines the height at which the illuminance values will be measured in the simulation. This information is stored in a Blender project (.blend file extension) which is later called by the simulation module.

- b) *IES files*. This type of file is the standard file format for the electronic transfer of photometric data (created by the Illuminating Engineering Society - IES [52]). They contain information about luminous flux and luminous intensity of luminaires. Based on this data, lighting simulation engines can compute the direction and intensity of the rays emitted by a specific light source and therefore, estimate the amount of light that hits a surface in a 3D space.
- c) *Minimum requirement grid*. This input consists of a rectilinear grid (regular topology and partially regular geometry) or an unstructured grid (irregular topology and irregular geometry). This grid can be interpreted as a copy of the calculation object but unlike the calculation object, it stores values that correspond to the minimum illuminance requirement for each functional unit as described in the international standards. In addition to the illuminance values, additional attributes can be assigned to each vertex/cell within this grid. These values are used later to evaluate the suitability of specific lighting alternatives using multiple criteria.

Simulation Engine

The electric lighting simulations are performed using RADIANCE [117], a physically-based rendering system developed by Greg Ward Larson at the Lawrence Berkeley National Laboratory, California. RADIANCE has been widely tested in many scenarios and up to date, it still proves to be one of the most accurate computational models for lighting simulation [92]. RADIANCE does not count with a native graphical user interface and the interaction with this package is mainly done by running a set of executable files from the command line. This fact poses a difficulty for its use for novice users and non-programmer users. However, due to the success and popularity of this package, it has been integrated into a large number of commercial and non-commercial 3D modeling software as is the case of Blender [15].

Blender is a free and open source 3D modeling application that integrates a large number of features for the creation of digital content. Among the features that make Blender suitable for its use in lighting simulation are: 1) Blender geometry is stored as a mesh, which makes it compatible with RADIANCE input files characteristics, and 2) Blender's API (Python2 Application Programming Interface) enables the easy and flexible manipulation and creation of functions and graphical user interface elements for the extension and specification of Blender's capabilities.

Taking advantage of these features, VI-Suite, an add-on for Blender developed by Ryan Southall at the University of Brighton, integrates a set of simulation and analysis tools (including RADIANCE) for the contextual and performative analysis of buildings [104]. In our case, this add-on serves as a pre/post processor for RADIANCE.

Within the Blender-VI-Suite environment a nodal interface supports the configuration of the simulation pipelines and parameters. An example of such network is depicted in Figure 3.3. The nodes required for a typical electric lighting simulation using RADIANCE are:

- *VI Location (input node)*: determines the geographical location of the building. Note that this is only used for performing daylight simulations where the position of the sun is computed based on this location (not used for electric lighting simulation but it is a requirement for the node-network).
- *LiVi Geometry (process node)*: this node transforms and exports the 3D model into a RADIANCE compatible model. The “result point” option establishes the point type used for the lighting metrics computation on the sensing plane (per vertex or per cell).
- *LiVi Context (process node)*: this node exports the lighting simulation context into a RADIANCE compatible context. The context includes the type of sky (not considered for artificial lighting simulations) and the metric to be calculated (basic context includes the metrics: illuminance, irradiance, daylight factor, and glare).
- *LiVi Simulation (analysis node)*: This node triggers the RADIANCE simulation given a valid geometry and context. This node allows controlling the level of accuracy of the simulation and the activation/de-activation of photon mapping.

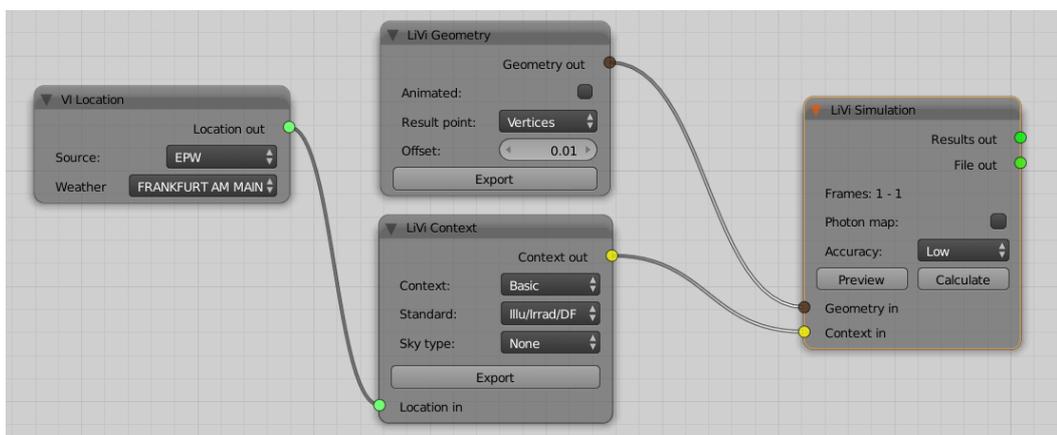


Fig. 3.3.: Simulation node-network configuration in Blender-VI-Suite version 0.3

The simulation node-network setup is performed once for each different factory layout or lighting arrangement. Once the full configuration is done (data input and simulation setup) the simulations are run offline (in batch) to avoid waiting times during the interactive exploration and comparison of multiple runs. The output of this process is a series of CSV files containing the illuminance values for each vertex/cell in the sensing plane. These files are later transformed to VTK Image to be further analyzed and visualized using the VTK Visualization Toolkit [46].

Analysis Engine

viPhos' analysis engine relies on a suite of data analytic tools based on common image processing techniques. The main operations included are image subtraction, mean absolute deviation, weighted difference, and percent error.

1. *Image Subtraction*. This approach is commonly used in image processing to visually enhance the differences between images. Here, we compute the absolute and non-absolute difference of the illuminance values between corresponding vertices/cells of two different lighting systems.

$$Q(i, j) = |P_1(i, j) - P_2(i, j)| \quad (3.1)$$

Where $P_1(i, j)$ and $P_2(i, j)$ two images to be compared (e.g., a reference image and a simulated image). As a result, we obtain a new image Q that once visualized, highlights the areas with larger or smaller differences in illuminance.

2. *Mean Absolute Deviation (MAD)*. We use MAD as a measure of similarity for illuminance distribution along a set of simulation runs and a reference distribution (minimum requirement grid). Based on this, we can determine, in average, how far is our set of solutions from the minimum requirement.

$$MAD_{Q(i, j)} = |P_{min}(i, j) - mean(P(i, j))| \quad (3.2)$$

Where $P_{min}(i, j)$ is the reference image (in this case, minimum illuminance requirement) and $mean(P(i, j))$ is the image resulting from computing the average illuminance for a set of simulated images.

3. *Weighted difference*. In this approach, an additional attribute to each vertex/cell of the minimum requirement grid is added. This attribute named “priority” describes the importance of the similarity in illuminance values between a lighting alternative (a single simulation run) and the minimum requirement grid. The weighting factor (defined by domain experts) is used to quantify the tolerance to deviations for different functional units. For example, visually-

demanding task areas have a higher priority than other areas. The result of this analysis is a ranking of the lighting alternatives with respect to their similarity to the reference configuration.

$$Q(i, j) = (P_1(i, j) - P_{min}(i, j)) * w_{min}(i, j) \quad (3.3)$$

Negative values in the resulting image Q indicate that the illuminance requirement has not been fulfilled in the location (i, j) . The magnitude of the difference expresses the importance or severity of this difference for that particular location.

4. *Percent error.* This metric compares the target values against the simulated values and express this difference as a percentage. A new image indicating this relative change per point in the calculation object is generated.

$$Q(i, j) = \frac{(P_1(i, j) - P_{min}(i, j))}{P_{min}(i, j)} * 100 \quad (3.4)$$

At the end of this stage, two different types of VTK images are generated: the ones resulting from the lighting simulation (output of Simulation Engine), and the ones resulting from applying any of the analysis approaches previously mentioned (output of Analysis Engine).

Visual Exploration Interface

viPhos visual exploration interface facilitates the analysis of raw and post-processed simulation results. The interface has three different views that support different phases of the analysis process. The visualization and interaction options offered by each of these views are described below.

Raw Results View: The raw results view consists of multiple coordinated viewports. The 3D viewports display color-coded images of the overall illuminance distribution for different lighting alternatives (color map and illuminance value range are shared along viewports). The 3D model of the factory layout is blended within the illuminance images to facilitate identification of visual obstacles and spatial orientation. The 2D viewport depicts line plots of the illuminance values along a cross-section highlighted in the 3D viewports. Dragging and dropping this cross-section triggers the update of the 2D plot showing values at different points in the factory layout. Figure 3.4 shows a schematic diagram of this view which, in turn, illustrates the visual comparison of two lighting alternatives (blue and magenta plot lines) against the minimum requirement grid (green plot line). The line plot shows the illuminance values across the interactive cross-section. In the illustrated example, none of the

two studied lighting alternatives fully satisfies the minimum illuminance values required in the region marked by the cross-section.

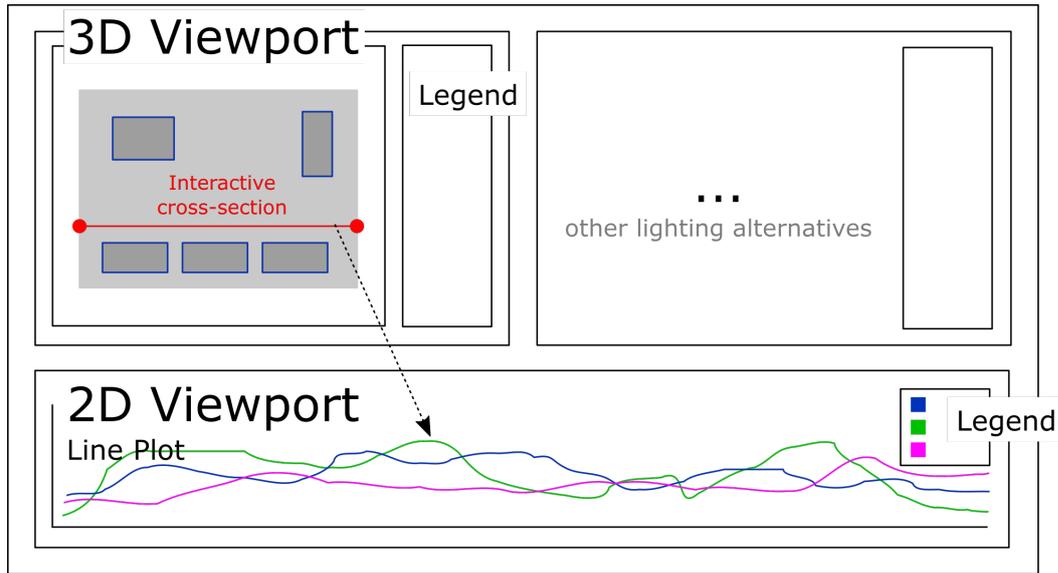


Fig. 3.4.: Schematic diagram of *viPhos*’ raw results view.

Difference View: As with the previous view, this view also consists of multiple coordinated viewports. The 3D viewports depict color-coded images encoding one of the available difference metrics (image subtraction or weighted difference). The special feature of this view is the ability to perform local analysis of lighting alternatives. This is possible via the direct manipulation of an interactive plane in the 3D viewport. Changes in the size and position of this interactive plane trigger an update of the 2D plot, which displays a histogram with the distribution of illuminance values in the highlighted region. Figure 3.5 shows a schematic diagram of this view.

Summary View: This view displays two color-coded images: the illuminance values stored in the minimum requirement grid (left) versus the MAD (Mean Absolute Deviation) computed for a set of simulations using the same SDL (right). The same technique of the interactive plane is applied here to compute the average illuminance for a particular region. Figure 3.6 shows a schematic diagram of this view. The text label located at the bottom of each image displays the average illuminance for the region inside the interactive plane.

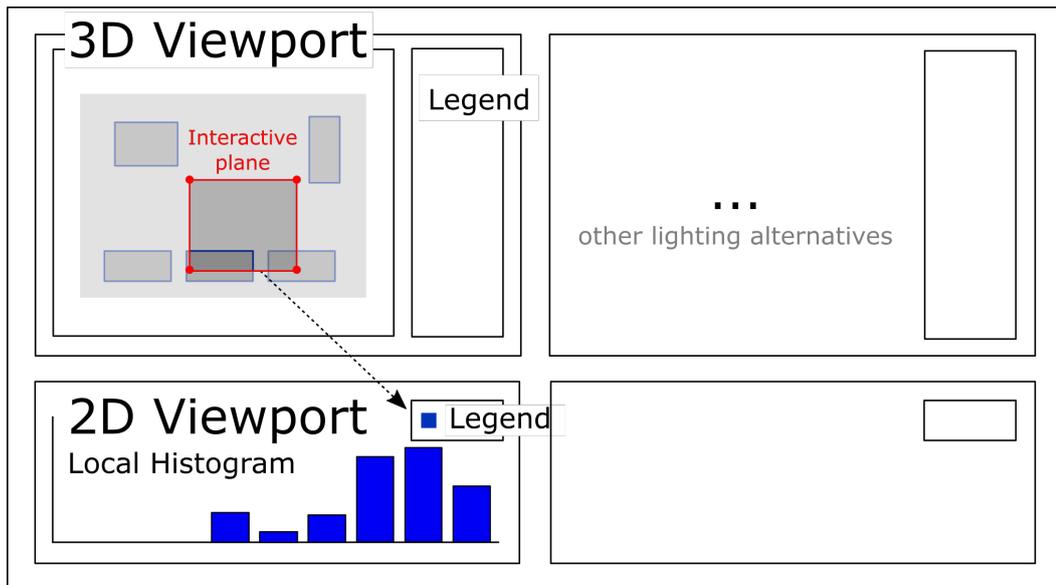


Fig. 3.5.: Schematic diagram of *viPhos*' difference view.

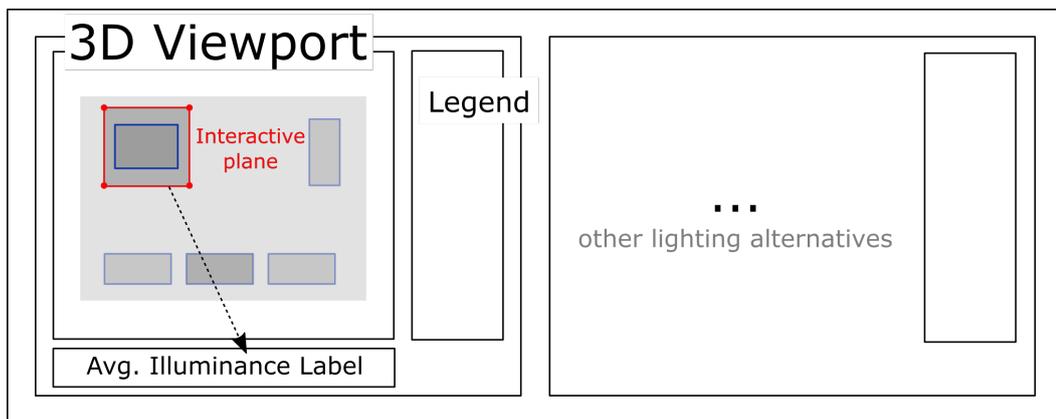


Fig. 3.6.: Schematic diagram of *viPhos*' summary view.

3.5 Case Studies using *viPhos*

3.5.1 CS1: Injection Molding Manufacturing Cell

In the injection molding process considered for this case study, first, raw material and molds are stored in a storage area. From that point, the raw material is transported to an injection molding area where the molds are mounted in the machines. The resulting pieces are then transported through a conveyor belt to a container, and later moved to a visual inspection area where they are examined for typical molding defects. Once the pieces have passed the inspection process, they are transferred to an assembly cell for their further processing. In addition, a mold production area consisting of two CNC machines works in parallel with the injection molding area.

Here, new molds are produced and to be used in the injection molding machines and later stored in the storage area.

In reference to the described operational layout, the manufacturing cell can be subdivided into four functional units: visual inspection, injection molding, storage, and mold production; which have been spatially distributed in order to favor inter-cell and intra-cell material handling. Figure 3.7 shows the physical layout design process of the injection plastic molding manufacturing cell. Top-left: schematic definition of the functional units. Top-middle: 2D layout design of the manufacturing cell. Top-right: rendered 3D model of the manufacturing cell. Bottom-left: details of the injection molding functional unit. Bottom-right: front view of a visual inspection workstation.

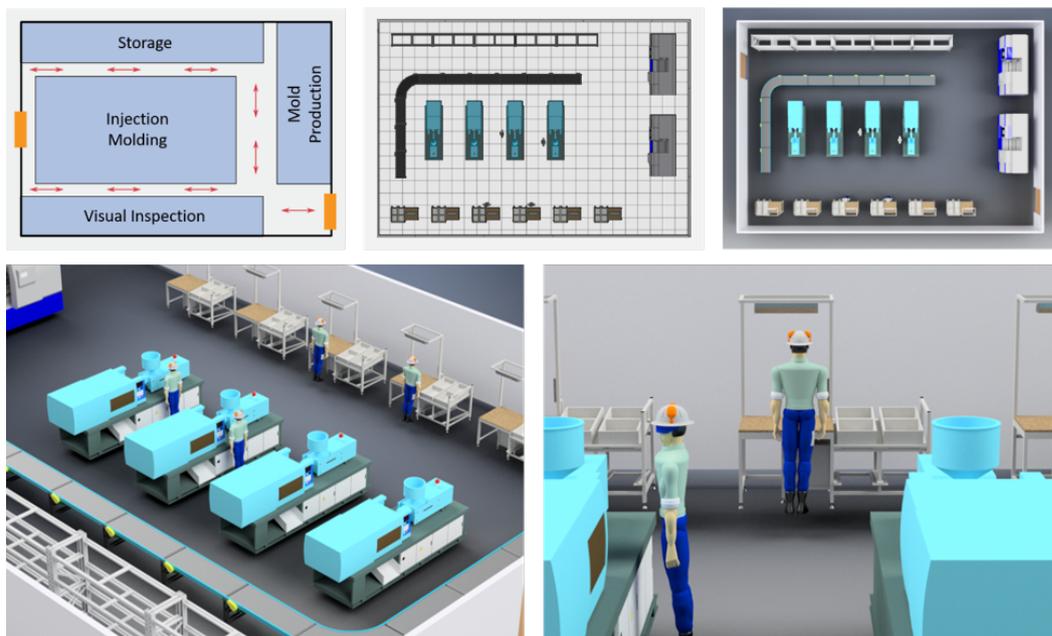


Fig. 3.7.: Physical layout of injection plastic molding manufacturing cell from the rough definition of functional units to the detailed 3D modeling of the interior and lighting distribution.

Tasks

Three experts including architects and lighting designers want to evaluate the performance of three types LED lamps to illuminate the different functional units in an injection molding manufacturing cell. Two different spatial distributions of the luminaires were prepared to evaluate which one is more suitable for the illumination of the cell. A particular interest is deposited in the analysis of the visual inspection functional unit, since the performance of workers in this area is critical for the quality of the manufactured parts.

In total six different lighting alternatives were simulated (three types of LED lamps simulated for two spatial distributions). By analyzing the simulation results, these experts wanted to obtain insights about the location and nature of critical areas as well as to identify the required modifications to the lighting design in order to fulfill the lighting standards for the type of visual task performed in each functional area. In conclusion, the goal of this analysis was to generate a refined lighting design that suits the needs of the functional units within the injection molding manufacturing cell.

Simulation setup

Lighting Requirements - EN 12464-1. The European standard EN 12464-1 “Lighting of workplaces – Indoor work places” was used as reference for this case study. This standard specifies requirements for lighting systems to ensure visual comfort and performance while performing different types of tasks. These requirements are expressed in terms of illuminance (E_m), upper limit for direct glare (UGR_L), uniformity (U_O), and lower limit for color rendering index (R_a). According to the standard, a workstation consists of two main “illuminance areas”: the task area and the immediate surrounding area (a strip of at least 0.5 m around the task area) for which particular maintained illuminance values are determined.

Type of task	Illuminance (E_m)	Immediate surroundings
Circulation areas and corridors	200 lux	150 lux
Store and stockrooms	100 lux	100 lux
Constantly manned work places in processing installations	300 lux	200 lux
Cutting, finishing, inspection	750 lux	500 lux
Color inspection	1000 lux	500 lux

Tab. 3.3.: Maintained illuminance requirements according to norm EN 12464-1.

Table 3.3 presents the maintained illuminance values required according to the types of task present in the injection molding manufacturing cell for working stations and the immediate surroundings. Based on the sketched rough and fine factory layouts and the values listed in Table 3.3, a base version of the minimum requirement grid was built. Each of the vertices that make up this grid was assigned with the minimum expected illuminance values corresponding to the functional units in the injection molding manufacturing cell (areas with no specific function are treated as circulation areas). Later on, a Gaussian filter was applied to this base grid to represent a smoother transition between task areas. Figure 3.8 illustrates the proposed task and immediate surrounding areas for the injection plastic molding manufacturing cell before and after applying the Gaussian filter. The images map

the maintained illuminance requirements for task areas and immediate surrounding areas according to EN 12464-1.

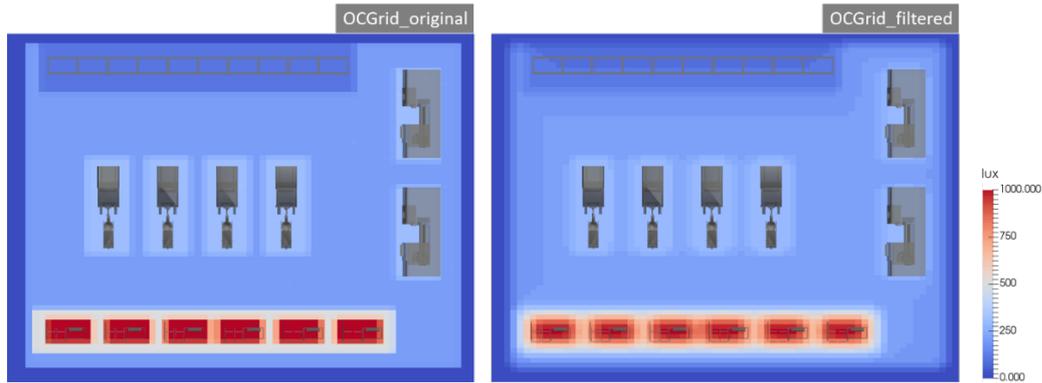


Fig. 3.8.: Minimum requirement grid before and after the smoothing transformation (Gaussian filter).

Lighting Technologies. Three LED luminaires produced by different manufacturers and used for industrial applications were selected for this case study. The main differences between these luminaires refer to the efficacy and initial delivered lumens. Table 3.4 shows the technical specifications of the selected luminaires.

	Alternative A	Alternative B	Alternative C
			
Product	2AVL2 AV LED	CR-LE_(1x4)_40L_100LPW	VTC-W L01148301
Manufacturer	Lithonia Lighting	CREE LED Lighting	Eclipse Lighting
Efficacy	85 LPW	100 LPW	117.4 LPW
Initial delivered lumens	2000 lumens	4000 lumens	8044 lumens
Input power	24 watts	22-50 watts	68.5 watts
CRI	not specified	90 CRI	74 CRI

Tab. 3.4.: Technical specification of the selected LED luminaires.

Spatial Distribution of Luminaires (SDL). Lighting layout designs depend on two aspects: the arrangement of functional units and the lighting requirements associated according to the type of task performed in each functional unit (as specified in reference standards). Considering these two aspects, two different luminaire layouts, represented as an array of rectangles, were prepared. A single luminaire is positioned

at the centroid of each rectangle, and hence the dimensions of the rectangles determine the proximity between luminaires. Figure 3.9 presents the two designs: a sparse configuration covering $\sim 66.76\%$ of the total manufacturing cell area (left), and a dense configuration with smaller rectangle sizes and a larger covering $\sim 83.23\%$ coverage of the total manufacturing cell area (right).

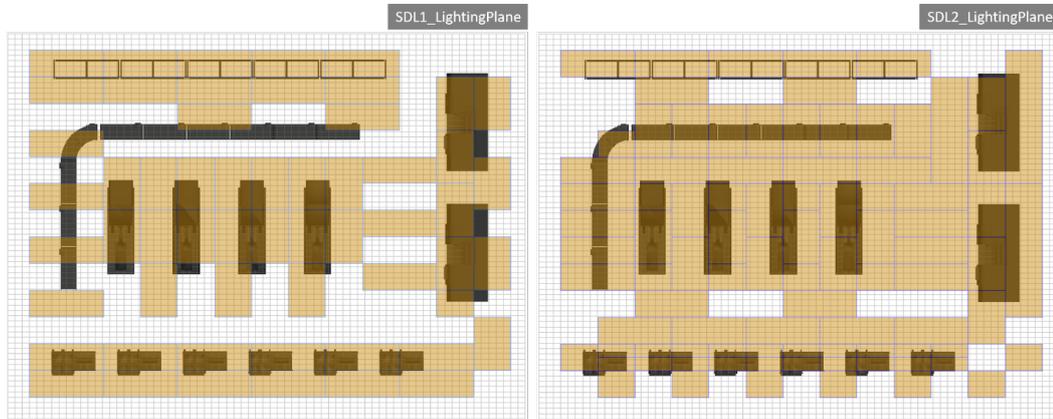


Fig. 3.9.: Studied spatial distributions of the luminaires. A luminaire is located at the center of each polygon defined in the lighting planes (shaded in orange).

Positioning of calculation objects. One calculation object (plane) was positioned at 0.9 meters height, which is the common height for the manipulation of objects in most of the workstations (except the storage area which has multiple shelves at different heights). Figure 3.10 shows a single resolution calculation object (modeled as a rectilinear grid - left) and a multiple resolution calculation object (modeled as an unstructured grid - right) assigned to the manufacturing cell.

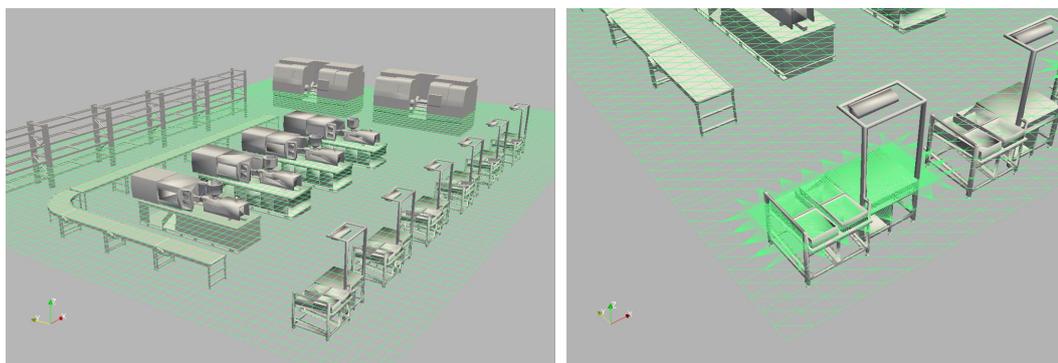


Fig. 3.10.: Calculation object for injection molding manufacturing cell positioned at 0.9 meters height. Left: single resolution grid. Right: multiple-resolution grid for detailed results in a visual inspection workstation.

Analysis

Three steps shape the analysis of the simulation results. First, the visualization of the raw results provide an overview of the illuminance distribution within the manufacturing cell for each lighting alternative. Then, each SDL configuration and its corresponding results are compared against the minimum requirement grid, and finally, a global metric comparing both SDL sets is studied.

Step 1: Visualization of raw simulation results.

To facilitate the visual comparison of single simulation results a common color map (blue - yellow) encoding illuminance values between 0-1000 lux was used. The dark blue region around the manufacturing cell area is a margin area outside of the walls surrounding the cell (the calculation object is bigger than the manufacturing cell area).

SDL1 – sparse configuration: Figure 3.11 shows the simulation results for the three different LED luminaires under the sparse configuration scenario. For all the alternatives simulated, the minimum illuminance required in the visual inspection area is not reached (1000 lux). The remaining functional units seem to be close or above the minimum illuminance requirement. The 2D plot over the visual inspection area shows that alternative C (Eclipse Lighting) performs slightly better than alternative B (CREE LED Lighting). However, in this case, alternative B is preferred since the CRI (Color Rendering Index) for this luminaire is considerably higher than for alternative C (90 vs. 74 respectively).

SDL2 – dense configuration: In contrast to the results of the SDL1 configuration, the dense configuration favors a better distribution of light among all functional units of the manufacturing cell. Figure 3.12 reveals more regions whose illuminance is closer to 1000 lux. For this SDL, the 2D plot over the visual inspection area proves that alternative B (CREE LED Lighting) has a slightly better performance. Despite this fact, there is not guarantee that these illuminance levels are appropriate for the particular tasks assigned to each functional unit of the manufacturing cell.

At first sight, it is difficult to point out the differences among lighting alternatives. From the visual exploration of the raw simulation results, the only thing that can be said is that the SDL2 seems to better cover the illuminance range required for the manufacturing cell in comparison to SDL1. However, from this “raw” view it is also not possible to determine whether a particular combination of SDL and luminaire fulfils the illuminance requirements of each functional unit. Therefore, the image subtraction approach was used to highlight the areas with major differences between the optimal configuration grid and the simulation results.

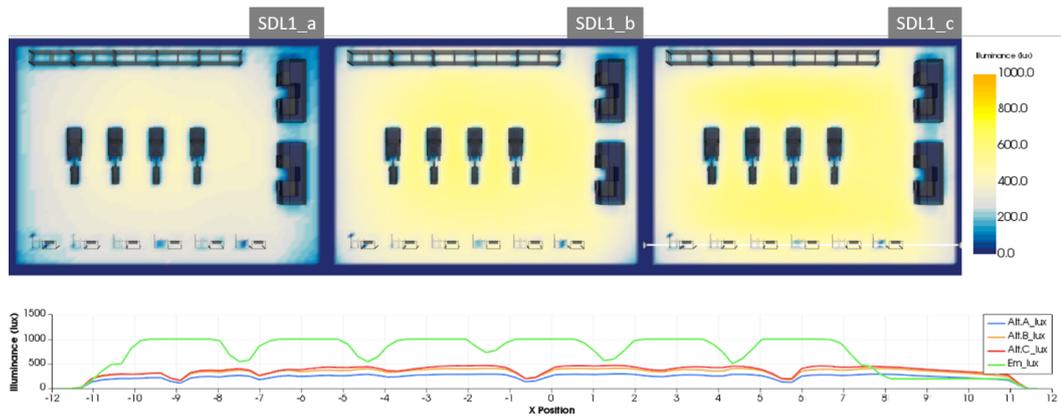


Fig. 3.11.: Simulation results for Spatial Luminaire Distribution 1 (SDL1) - sparse configuration for the three LED luminaires.

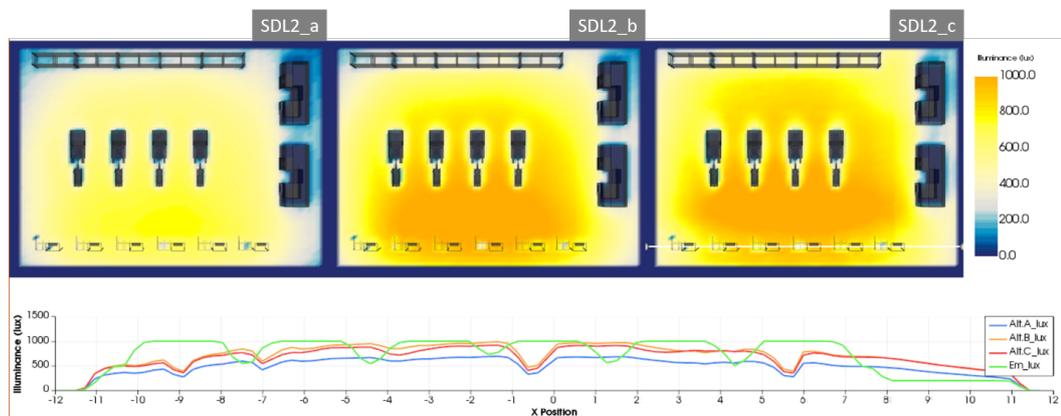


Fig. 3.12.: Simulation results for Spatial Distribution of Luminaires 2 (SDL2) – dense configuration for the three LED luminaires.

Step 2: Comparison of simulation results against EN 12464-1.

Figures 3.13 and 3.14 illustrate the deviation of each simulation run with respect to the minimum requirement grid. A negative deviation (orange) represents regions where the illuminance is higher than the minimum required while a positive deviation (purple) represents regions where the illuminance is lower than the minimum required. A summary visualization depicting the mean difference between the three lighting alternatives corresponding to each SDL and the optimal configuration grid is shown in the upper left corner of the figures to help experts analyzing the overall SDL design.

SDL1 – sparse configuration: Under this SDL, alternative A (Lithonia Lighting luminaire) shows the smallest deviation to the minimum requirement grid except for the visual inspection area where the illuminance values are much lower (areas highlighted in purple). On the other hand, alternative C (Eclipse Lighting) seems to have the smallest deviation in the visual inspection area in

contrast to the other two alternatives. A closer look to the lighting alternative C using the local illuminance histogram (Figure 3.15 - left) reveals that the illuminance in most of the visual inspection area does not surpass 500 lux.

SDL2 – dense configuration: In this configuration, the three lighting alternatives surpass for over 250 lux the minimum illuminance requirement for all functional units of the manufacturing cell except the visual inspection area. Despite the increase in the illuminance levels, there are still critical spots uncovered. Once more, alternative C (Eclipse Lighting) shows the smallest positive deviation to the minimum requirement grid. Further local analysis performed using the local histograms technique along with the multiple resolution grid for the calculation object (Figure 3.15) exposes that alternative C under this SDL is more suitable but still not optimal for the type of task in the visual inspection area.



Fig. 3.13.: Comparison of simulation results for SDL1 against the minimum requirement grid.

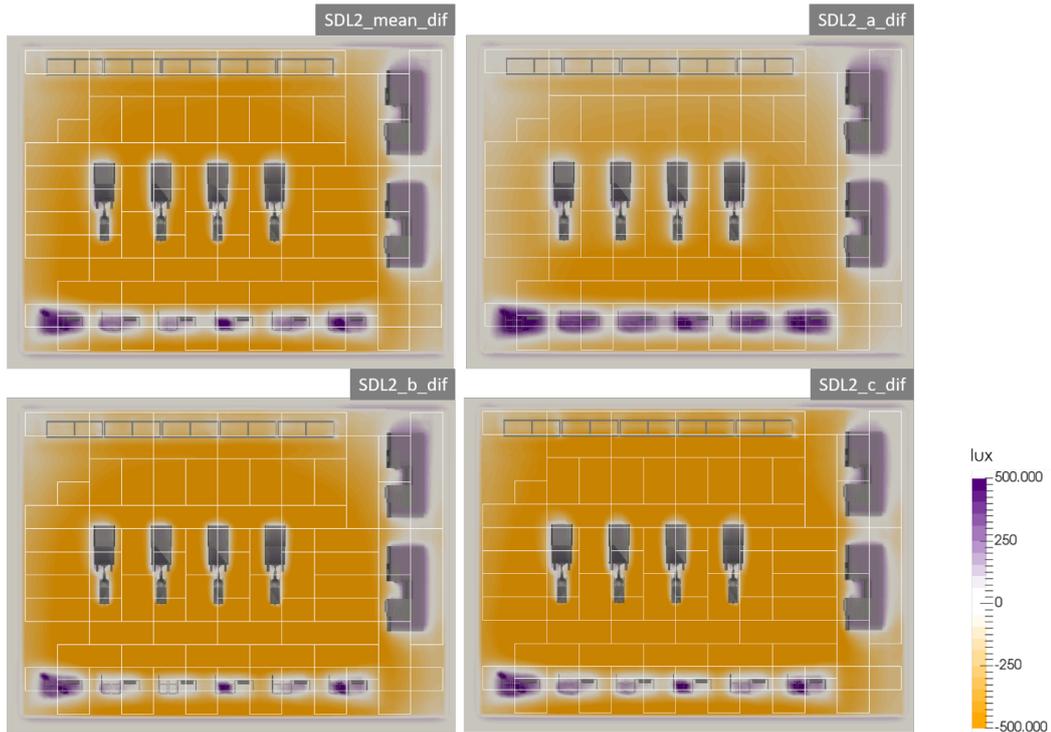


Fig. 3.14.: Comparison of simulation results for SDL2 against the minimum requirement grid.

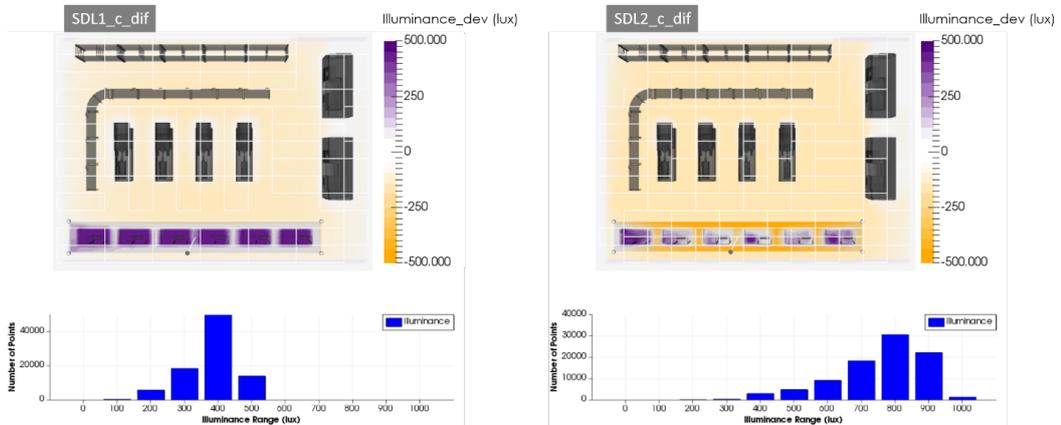


Fig. 3.15.: Difference view for lighting alternative C under SDL1 (right) and SDL2 (left).

Step 3: Summary View for Spatial Luminaire Distributions.

The Mean Absolute Deviation technique is used to provide a global metric for the assessment of both SDLs. Figures 3.16 and 3.17 depict the Mean Deviation Metric for both sets of simulations. In addition, the computation of local average illuminance, when enabled through the interactive plane, provides more details about the performance of an SDL in specific functional units or workstations. Although SDL1 has the smallest global deviation from the optimal configuration grid, it has the largest local deviation in the visual inspection area. This is a critical pitfall due

to the type of task performed in this area. The local average illuminance calculated for one of the visual inspection workstations shows a difference of ~290 lux for SDL1 and ~569 lux for SDL2.

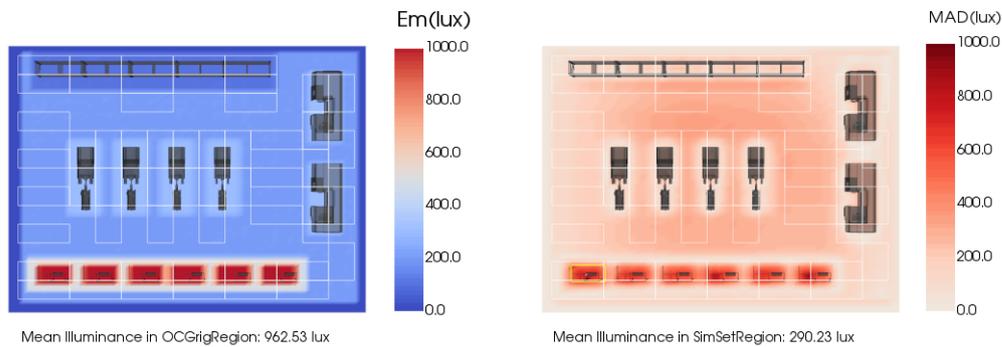


Fig. 3.16.: Mean Absolute Deviation to the minimum requirements grid computed for the set of simulations under SDL1.

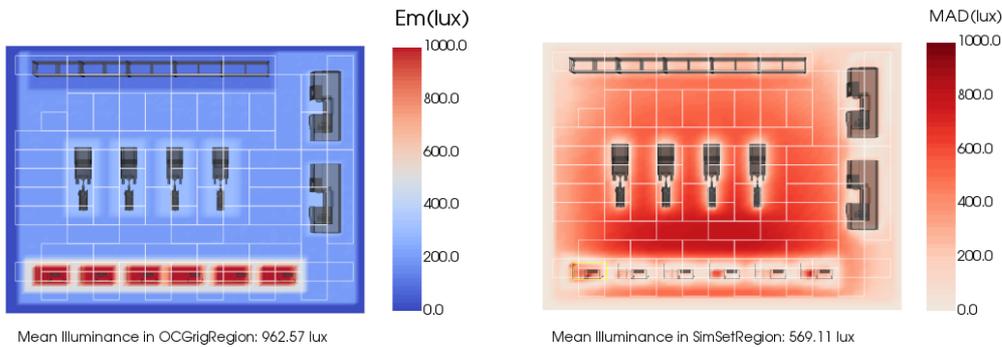


Fig. 3.17.: Mean Absolute Deviation to the minimum requirements grid computed for the set of simulations under SDL1.

Discussion

Based on the visualization and analysis of the lighting alternatives, three options to correct the lack of lighting in one of the most critical functional units of the manufacturing cell (visual inspection area) were formulated. For each of the three options a new analysis cycle (input data, simulation, analysis and visualization) was performed.

Option 1: Redesign of the SDL to have a denser configuration in the visual inspection area preserving luminaire B (CREE LED Lighting) in this region due to its advantageous technical properties (high CRI and lower energy consumption).

Option 2: Apply a mixed approach to optimize both, the SDL and the luminaire for the visual inspection area. This means, considering multiple types of luminaires as well as changing the geometry of the SDL.

Option 3: Select and evaluate a new set of luminaires with different technical specifications.

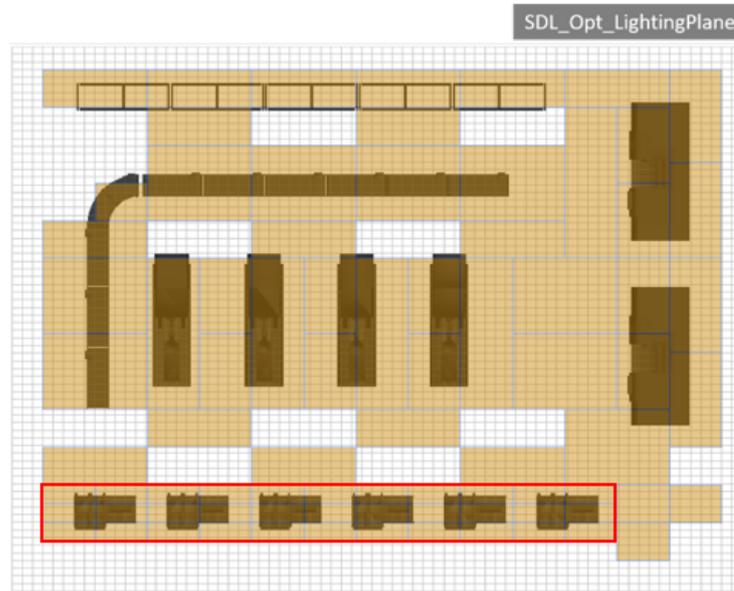


Fig. 3.18.: Redesign of SDL with the purpose to decrease the excess of light in the circulation areas (in comparison to the simulation results for SDL2 – Luminaire B) and increase the illuminance in the visual inspection area.

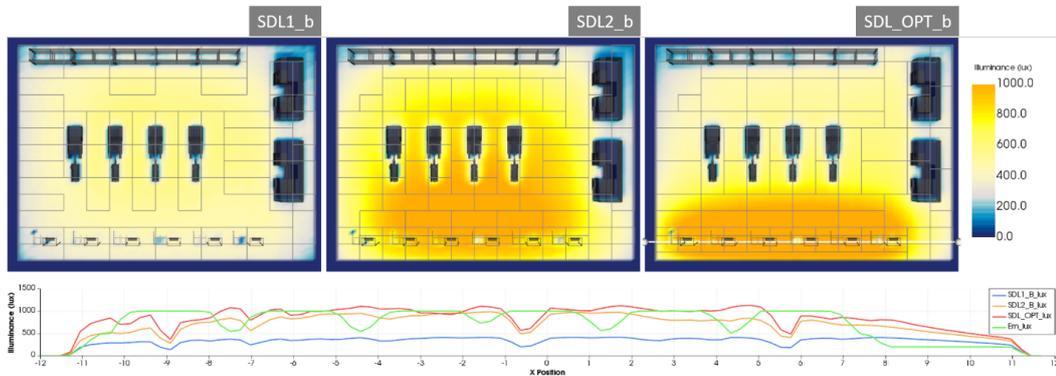


Fig. 3.19.: Comparison of the initial SDL designs vs. the optimized SDL design using the raw results view.

In this case, Option 1 was selected. Two major changes in the design of the new SDL were introduced: 1) density of the luminaires and 2) height of the luminaires dedicated to the visual inspection area (from 5.5 meters to 4.5 meters - enclosed in a red rectangle in Figure 3.18). Figure 3.19 presents the comparison of the initial SDL designs vs. the optimized SDL design using the raw results view. The simulation

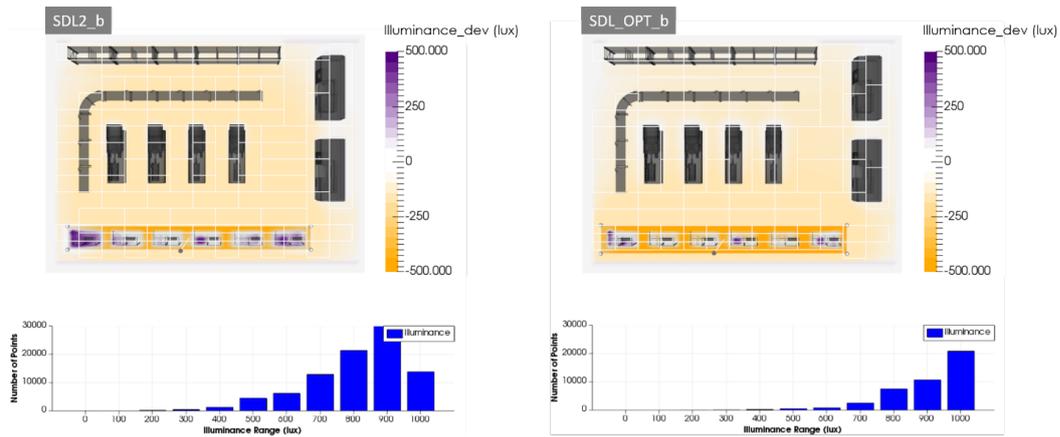


Fig. 3.20.: Deviation from minimum requirement grid to simulation results of the optimized SDL.

results for the optimized lighting design (right) shows a decrease of illuminance levels for the circulation areas and an increase of illuminance levels in the visual inspection area. Figure 3.20 presents the analysis of the new simulation results using the difference view. The local histogram view reveals a significant variation in the illuminance distribution in comparison to SDL2_b.

3.5.2 CS2: Road Work Zones

Recently, several studies have been dedicated to analyze the impact on visual performance and glare perception that the use of different types of lighting technologies have on nighttime road work zones [14, 20]. LED lighting has been categorized as an attractive choice due to its advantages with respect to efficiency, durability, and portability among other characteristics.

The most common technique to analyze how a lighting technology will perform at a road work zone is to carry out experimental studies. In these experiments, metrics such as illuminance, luminance, glare, and others are evaluated quantitatively and qualitatively. The costs of performing these experimental studies are very high considering that the equipment has to be owned or rented, it is difficult to reproduce special conditions present in real working areas, and also, they lack flexibility for cases in which latest lighting technologies NEED to be tested. Hence, simulation is a valuable alternative to overcome these obstacles.

To study the applicability of solar-powered LED lighting for road work zones a simulation-based analysis was performed. A 3D scenario of a work zone was created and tested by simulating the lighting conditions using experimental illuminance measurements for different types of lights commonly used in nighttime work zones.

Scenario

With the guidance of experts in road work from the University of California – Davis, a 3D virtual scenario of an entire road work zone was modeled for the simulation-based evaluation of solar-powered LED lighting. The scenario is based on one of the typical applications for temporary traffic control described in the California MUTCD [108]: lane closure on two-lane road using flaggers. It consists of a road work zone of 300 ft. (91.44 m.) length within a two-lane road (one lane in each direction). Tapers are 50 ft. (15.24 m.) length at each end of the closure and flagger stations are positioned at the beginning or end of these tapers. Figure 3.21 illustrates the work zone and flagger station segments proposed for the simulation.

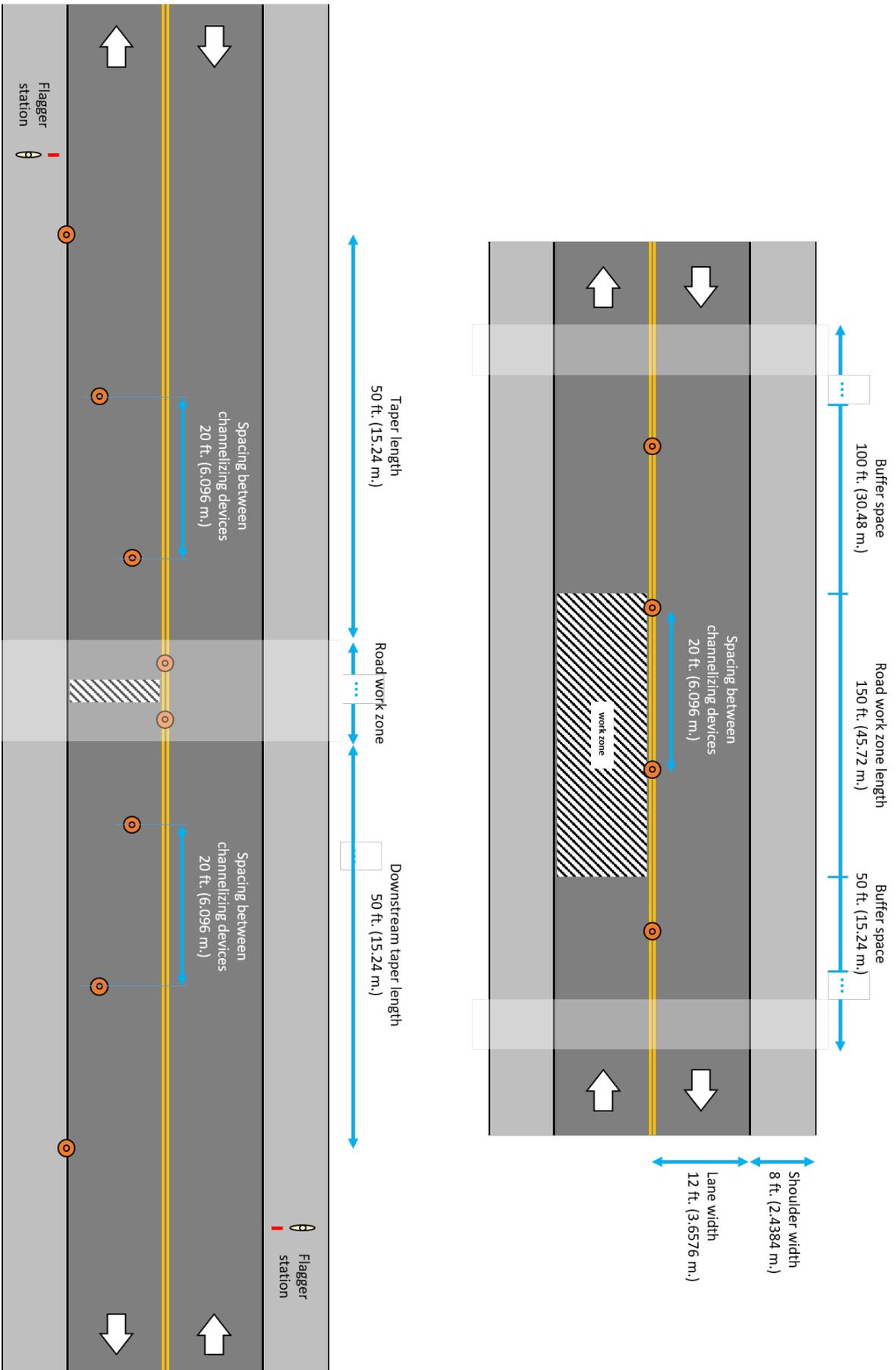


Fig. 3.21.: Road work zone dimensions (top) and taper and flagger station dimensions used for simulation (bottom).

Tasks

Researchers of the Advanced Highway Maintenance & Construction Technology Research Center (AHMCT) at University of California – Davis wanted to investigate the feasibility of using a fully-solar-powered fleet of LED light towers to illuminate an entire road work zone. The motivation emerged after performing an extensive evaluation and comparison of this technology versus the commonly used diesel-powered metal halide light towers [84]. Thus, this case study presents a simulation-based evaluation of the performance of LED versus metal halide light towers with respect to illuminance and light uniformity.

Simulation setup

Lighting Standards for Nighttime Road Work Zones. For this scenario, the illuminance levels for nighttime road work recommended by the National Cooperative Highway Research Program (NCHRP) [37] were considered. Three different categories can be distinguished depending on the precision and visual acuity required for different tasks. Category I: 5 Foot-Candles (54 lux); Category II: 10 Foot-Candles (108 lux); and Category III: 20 Foot-Candles (216 lux). Table 3.5 provides exemplary tasks for each category. Figure 3.22 depicts the proposed segmentation of the entire road work zone by categories.

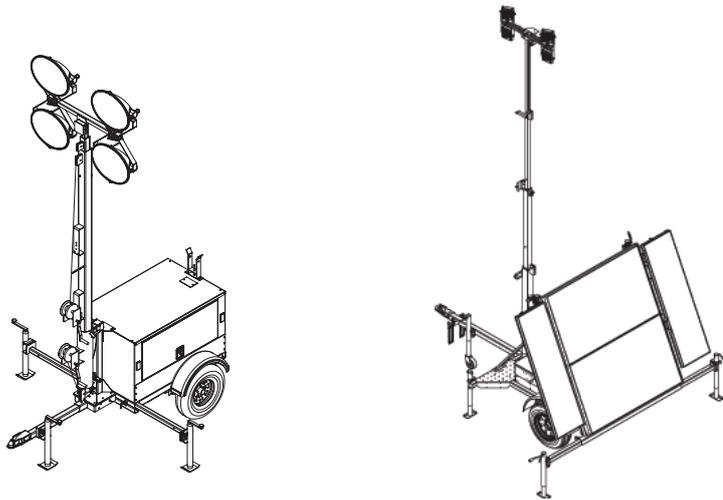
Description of construction and maintenance task	Average maintained Illumination	
	Category	Target Level
<ul style="list-style-type: none">Asphalt pavement rollingReworking shouldersSweeping and cleaning	I	54 lux (5 fc.)
<ul style="list-style-type: none">Asphalt paving and resurfacingMilling removal of pavementRepair of concrete pavement	II	108 lux (10 fc.)
<ul style="list-style-type: none">Crack fillingInstallation of traffic signalsInstallation of highway lighting systems	III	216 lux (20 fc.)

Tab. 3.5.: NCHRP recommended maintained illuminance levels for different tasks.



Fig. 3.22.: Minimum illuminance requirement grid for modeled road work zone.

Lighting Technologies. Both, diesel-powered and solar-powered light towers were modeled based on the description of commercially available light towers (Magnum Power Products LLC. (diesel-powered, metal halide) and Wanco Inc. (solar-powered, LED)). The technical specifications and photometric data files of the lamps used in these light towers were taken from the study performed by [84]. Details about these specifications are described in Table 3.6.



	Magnum MLT 3060 (diesel-powered)	Wanco Medium Solar Light Tower
Description	Metal Halide, 4 x 1000 W Rated 440,000 lumen 6 kW output 30 ft. (9.144 m.) Weight 1820 lb.*	LED, 8 x 48 W @ 24 V Rated 36,800 lumen 20 ft. (6.096 m.) 890 W solar panels 8 4D batteries, 200 Ah at 12V Weight 1900 lb.
Deployed with Outriggers L x W	117 in. (297.18 cm.) x 96 in. (243 cm.)	181 in. (460 cm.) x 111 in. (282 cm.)

* Drawings taken from product brochures

Tab. 3.6.: Light towers and lamps' specifications used in experiments from [84].

Spatial Distribution of Light Towers and Lamps. In order to cover the actual work zone (150 ft. or 45.72 m.), a total of 6 light towers were positioned equidistant from one another (each at 42.5 ft. or 129.54 m.). This number of light towers proved to be ideal for a relatively uniform coverage of the complete work zone. The light

towers were configured to be deployed with 17.5 ft. (5.33 m.) height from the road surface.

In the modeled scenario, 5 of the 6 light towers have the same tilt and orientation configuration for the 4 lamps. The other tower has a slight variation in tilt and orientation with the purpose to recreate a focused work area. Table 3.7 describes the tilt and orientation used in both cases.

Lamp 1	Lamp 2	Lamp 3	Lamp 4
(53 °, -60 °)	(53 °, -15 °)	(53 °, 15 °)	(53 °, 60 °)
(53 °, -45 °)	(53 °, -15 °)	(53 °, 15 °)	(53 °, 45 °)

Tab. 3.7.: From left to right - front view. Tilt and orientation of each lamp in the light tower. Row 1 - general configuration. Row 2 - focused work area.

Two flagger stations, modeled at the beginning and the end of the road closures, are equipped with balloon lights and they were deployed at 15 ft. (4.572 m.) height.

Positioning of calculation objects. One calculation object (plane) was positioned at 0.03 ft. (0.01 m.) height from the road surface. Figure 3.23 shows the calculation object (modeled as a triangular grid) assigned to the road work zone. Additional calculation objects can be positioned to store simulation results in other planes (e.g., to evaluate vertical illuminance).

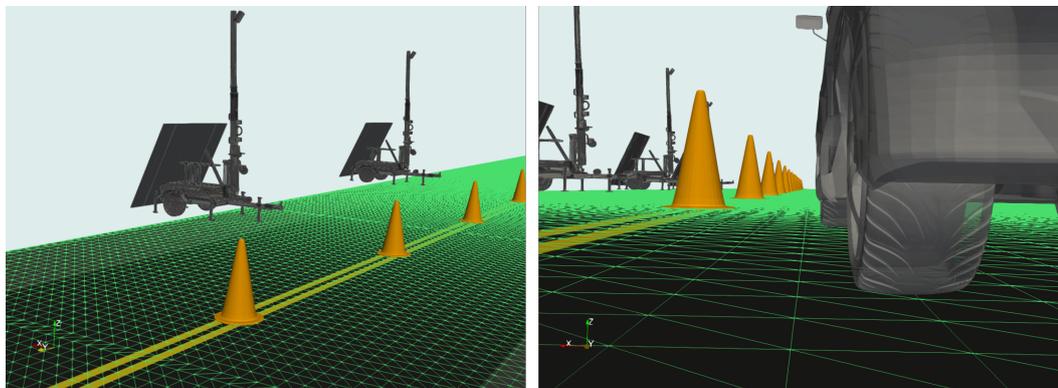


Fig. 3.23.: Calculation object for road work zone positioned at 0.03 ft. (0.01 m.) height.

Analysis

The analysis of the simulation results for this case study consists of three steps: 1) visualization of the raw results as an overview of the illuminance distribution, 2) comparison of the results against the minimum requirement grid, and 3) uniformity analysis to evaluate the lighting alternatives.

Step 1: Visualization of raw simulation results.

To facilitate the visual comparison of single simulation results a common color map (blue - yellow) encoding illuminance values between 0-500 lux was used.

Metal Halide Lamps: Figures 3.24 and 3.25 (top) show the simulation results for the diesel-powered light towers using metal halide lamps. In this scenario it is possible to see that the illumination in the work zone (marked between the inner green lines) is above the illuminance recommendations even for the most demanding visual tasks (216 lux). However, high illuminance levels reach the operating lane which might have a negative impact on motorists (in terms of glare perception).

LED Lamps: The simulation results for the solar-powered light towers using LED lamps shown in Figures 3.24 and 3.25 (bottom), evidence that the illuminance levels in most regions within the work zone is between 100 and 300 lux. Although illuminance levels in this scenario are considerably lower than for the metal halide lamps, the minimum illuminance requirement for the designated visual tasks is still fulfilled (≥ 108 lux). Another aspect that was noticed is that in this scenario, the operating lane is much less affected by the light sources which has a great impact on the perceived glare by motorists.

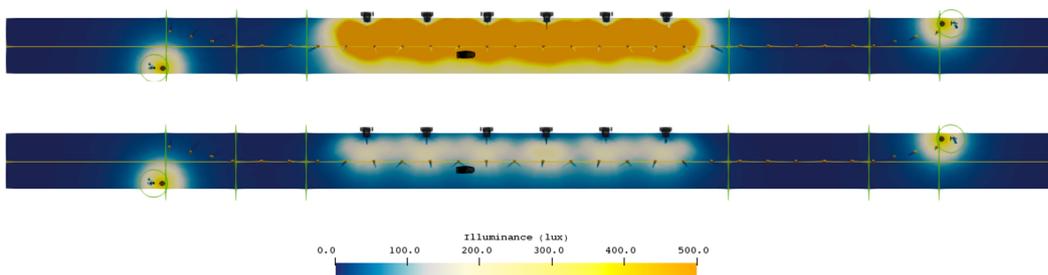


Fig. 3.24.: Simulation results for diesel-powered light towers (using metal halide lamps) (top) and solar-powered light towers (using LED lamps) (bottom).

In both scenarios, the balloon light used for the flagger stations consists of a single metal halide bulb which emits light in all directions, therefore there is no difference in the simulation results from one scenario to the other. Figures 3.24 and 3.26 depict the simulation results for the flagger stations located at the beginning and end of the road closure. The results show that the illuminance levels for a surrounding area a radius of 20 ft. (6.096 m.), as specified in the standards, is adequately covered to guarantee flaggers' visibility.

Step 2: Comparison of simulation results against California MUTCD.

Prior to the comparative analysis, rendered views showing the motorists' and workers' points of view were generated to give researchers an initial idea of the difference between both scenarios. A first qualitative analysis based on the pictures in Figure

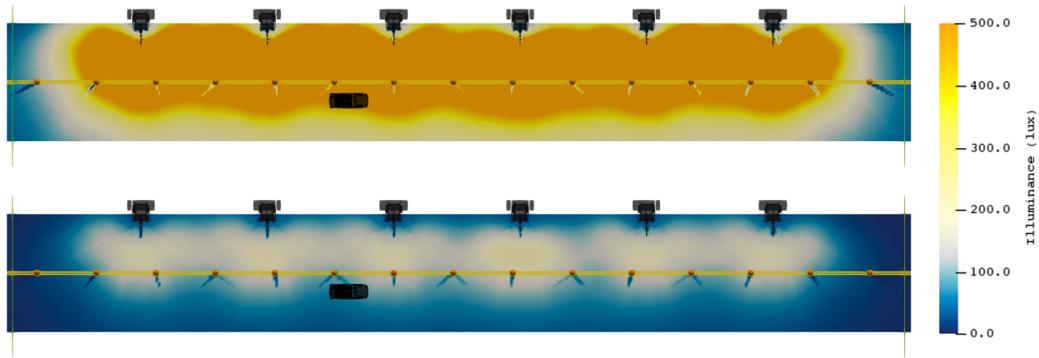


Fig. 3.25.: Close-up of simulation results in work area for diesel-powered light towers (using metal halide lamps) (top) and solar-powered light towers (using LED lamps) (bottom).

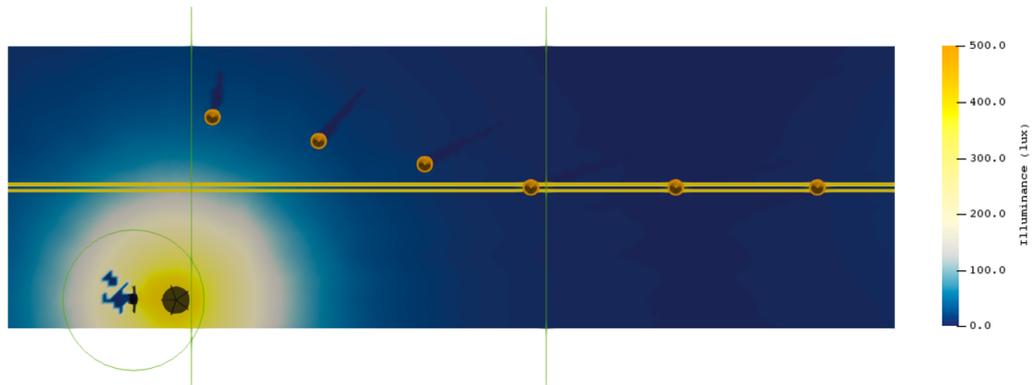


Fig. 3.26.: Close-up of simulation results of flagger stations.

3.27 clearly shows that diesel-powered light towers (using metal halide lamps) provide a higher intensity in lighting than the solar-powered light towers (using LED lamps). Even if this seems to be more adequate at first sight, the quantitative analysis of the simulation results demonstrated that this is not always the case.

For the quantitative comparative study, two filters have been incorporated into the analysis engine of *viPhos*. The first one resembles a binary image in which regions that pass/fail the requirement are colored in green and red respectively. This strategy facilitates the fast identification of potentially problematic areas within the road work zone. The second one computes the relative difference between the simulation results and the minimum requirements grid. The resulting image depicts as a percentage the regions within the road work zone that fulfill the requirement with a single color (gray), while regions that do not fulfill the requirement are depicted using a color map between orange and purple indicating the magnitude of the difference as a percentage.

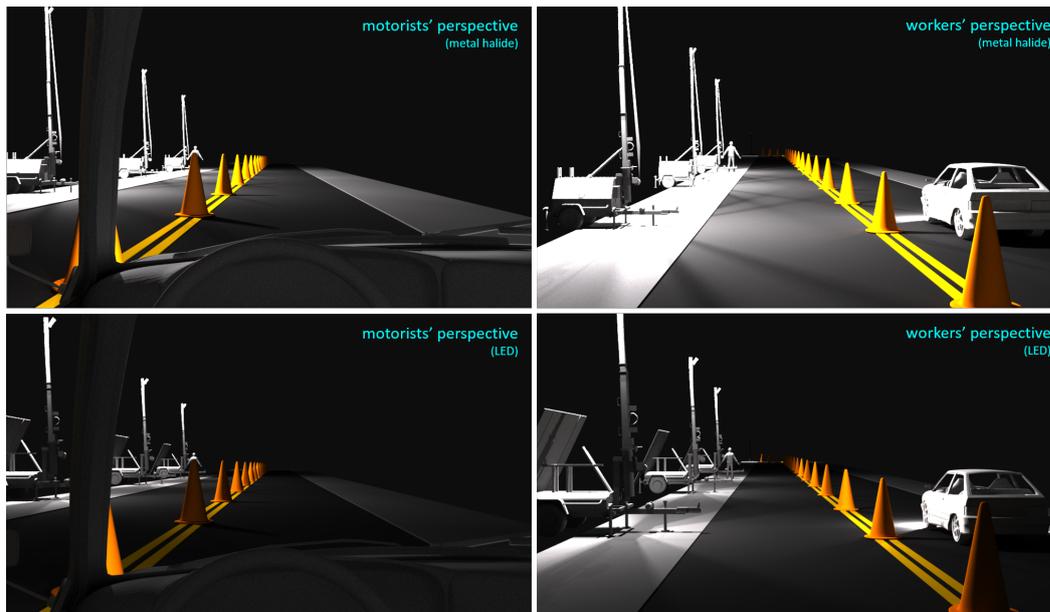


Fig. 3.27.: Rendered views from motorists' perspective and workers' perspective for both diesel-powered light towers (using metal halide lamps) (top row) and solar-powered light towers (using LED lamps) (bottom row).

Metal Halide Lamps: Based on the visualization of pass/fail regions shown in Figure 3.28 (top), it is possible to conclude that the illumination provided by the diesel-powered light towers using metal halide lamps satisfies, in most areas, the requirements established in Figure 3.22. Figure 3.29 (top) provides a detailed view of the magnitude of the differences as percentages. Consistently with the pass/fail analysis, only very small regions at the lower corners of the actual work area and the left flagger station reveal a difference that does not exceed by 50% the illuminance requirement.

LED Lamps: In the case of the solar-powered light towers using LED lamps, Figure 3.28 (bottom) highlights two large red regions at the beginning and the end of the actual road work zone. A detailed view on the magnitude of the differences in these regions (Figure 3.29 (bottom)) reveals that in some cases the relative difference reaches up to 200% the minimum illuminance requirement. For the sub-regions laying on the operating lane and shoulders area, this fact is not considered as a hazard taking into account that workers' visual tasks are not compromised.

Further exploration using the difference view, shows the local distribution of the relative difference between the minimum illuminance requirement and the simulation results for both scenarios (Figure 3.30). In the solar-powered light towers scenario, the local analysis of a sub-region where the largest illuminance deviations appear reveals that the relative difference goes up to 120% of the minimum illuminance

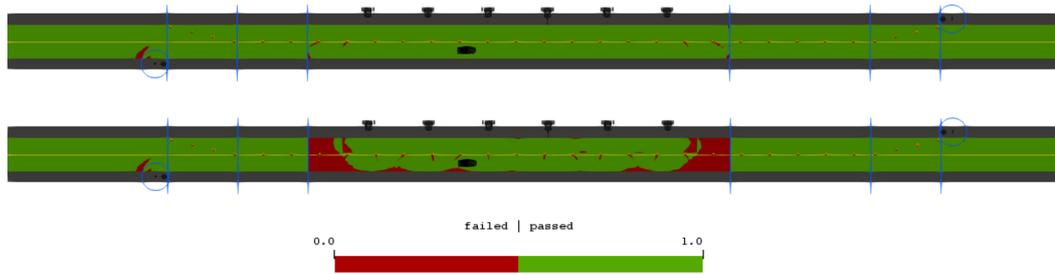


Fig. 3.28.: Pass/fail regions for diesel-powered light towers (using metal halide lamps) (top) and solar-powered light towers (using LED lamps) (bottom).

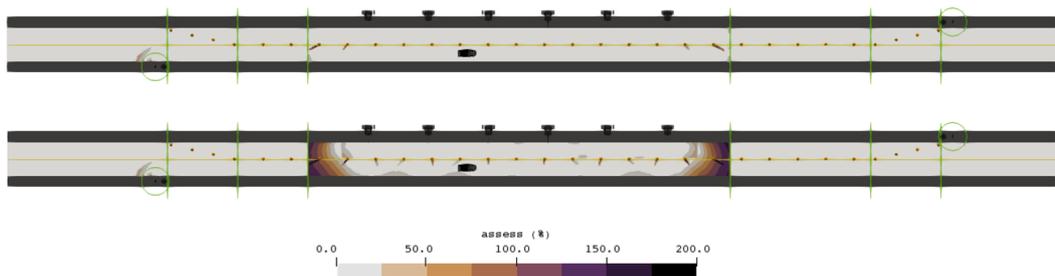


Fig. 3.29.: Relative difference between simulation results for diesel-powered light towers (using metal halide lamps) (top) and solar-powered light towers (using LED lamps) (bottom) with respect to minimum requirement grid.

requirement in the darkest regions (colored dark purple). This can represent a hazard when particular visual tasks need to be performed in these areas, however, this issue can be easily tackled by shifting the light towers as the road work progresses in either of the two directions.

Step 3: Uniformity analysis.

Another aspect that plays an important role in any lighting scenario is uniformity. Uniformity refers to how evenly light spreads over a task area. Ideally, there should not be any great differences in brightness since this can cause extreme eye discomfort and therefore lead to accidents in the road work zone or on the operating lane. There are several approaches to evaluate uniformity, for example: [50, 85]. In this case study the average-to-minimum metric is used for the first part of the analysis followed by the gradient magnitude of the illuminance for a more detailed analysis of uniformity.

Figure 3.31 depicts the average-to-minimum uniformity ratio calculated for a specific area of the road work zone. According to different standards and recommendations [37, 51], this ratio ranges between 3:1 and 6:1, the lower the ratio the better the uniformity. The interactive capabilities offered by the summary view allow the interactive selection of local regions. As the interactive plane is resized and repositioned this uniformity metric is calculated.

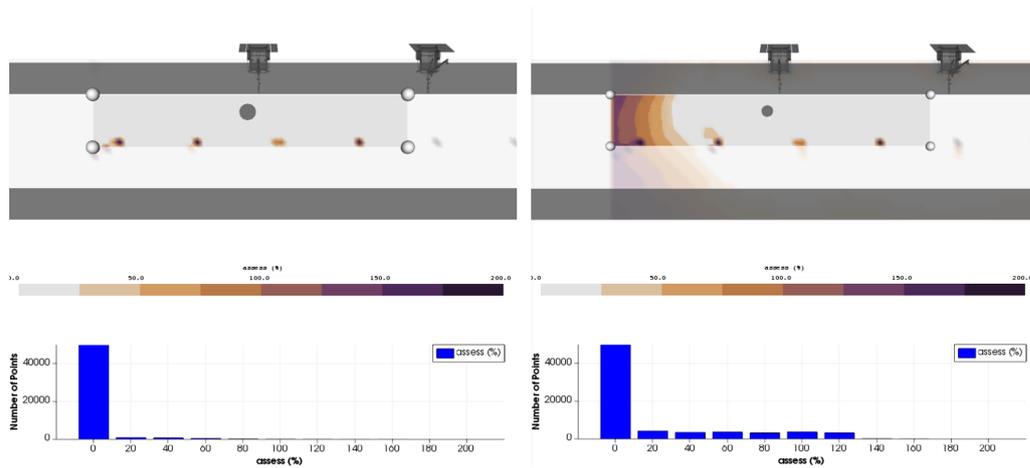


Fig. 3.30.: Difference view for diesel-powered light towers (using metal halide lamps) (left) and solar-powered light towers (using LED lamps) (right).

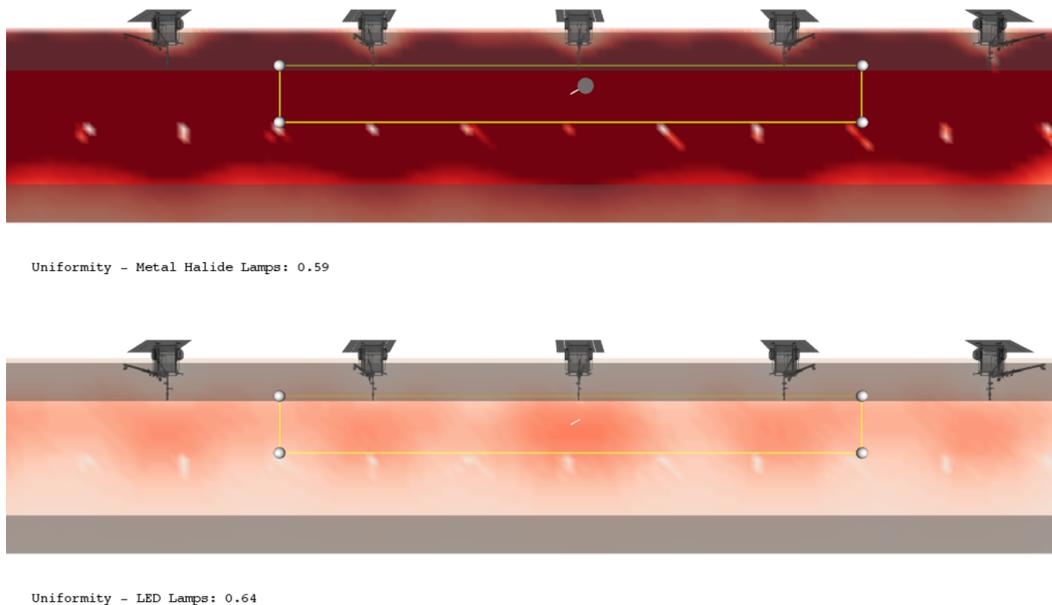


Fig. 3.31.: Average-to-minimum uniformity ratio computed for sub-region inside the road work zone. Top: diesel-powered light towers (using metal halide lamps). Bottom: solar-powered light towers (using LED lamps).

Even when the common uniformity ratio (average-to-minimum) gives an indication of how even is the lighting in a task area, it becomes cumbersome to identify local hazards that might be caused by uneven lighting. To address this problem, a second approach that evaluates local uniformity using gradient information was applied. Figure 3.32 depicts the gradient of the illuminance for both scenarios. The arrow glyphs point at the direction of the greatest rate of change in illuminance and the background color map indicates the magnitude of this change. For the scenario with

solar-powered light towers using LED lamps, sharp changes in illuminance appear next to the signaling devices. This is mostly produced by the shadow produced by these objects. In the scenario with diesel-powered light towers using metal halide lamps, there are significantly greater changes in the areas directly surrounding the light towers. This might have an impact on the perceived visual comfort for punctual visual tasks within the road work zone.

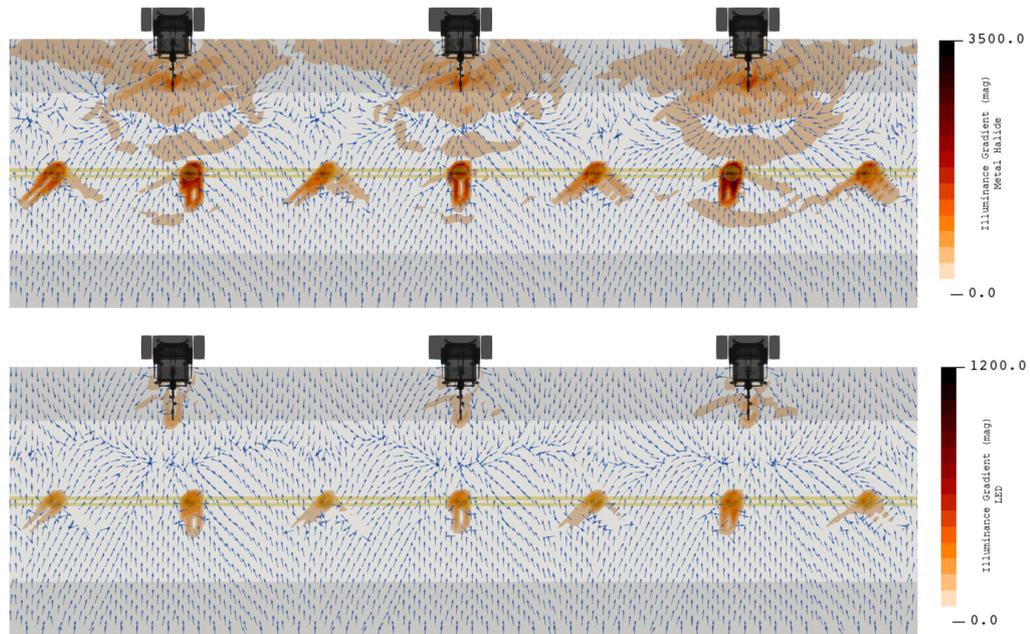


Fig. 3.32.: Gradient of the illuminance at road work area for diesel-powered light towers (using metal halide lamps) (top) and solar-powered light towers (using LED lamps) (bottom).

Discussion

The analysis of the simulation results demonstrates that solar-powered light towers using LED lamps can be considered as an alternative for the illumination of night time road work zones. Besides the economic and environmental advantages that this alternative represents, particular aspects related to the uniformity and perception of glare addressed in this analysis also indicate that this configuration favors the visual comfort of workers and motorists. Although the modeled metal halide lamps provide about 4 times the light intensity of LED lamps, the distribution of the solar-powered light towers along with the LED lamps proved to be sufficient for the performance of the designated visual tasks.

After the identification of the poorly illuminated regions at the beginning and the end of the actual road work zone, one additional lamp has been attached to the first and last light towers. The simulation results after this modification show that the

new alternative provides a better coverage of these regions without compromising the illuminance uniformity. Figure 3.33 shows the visualizations of the relative difference between the original and new configurations with respect to the minimum requirement grid.

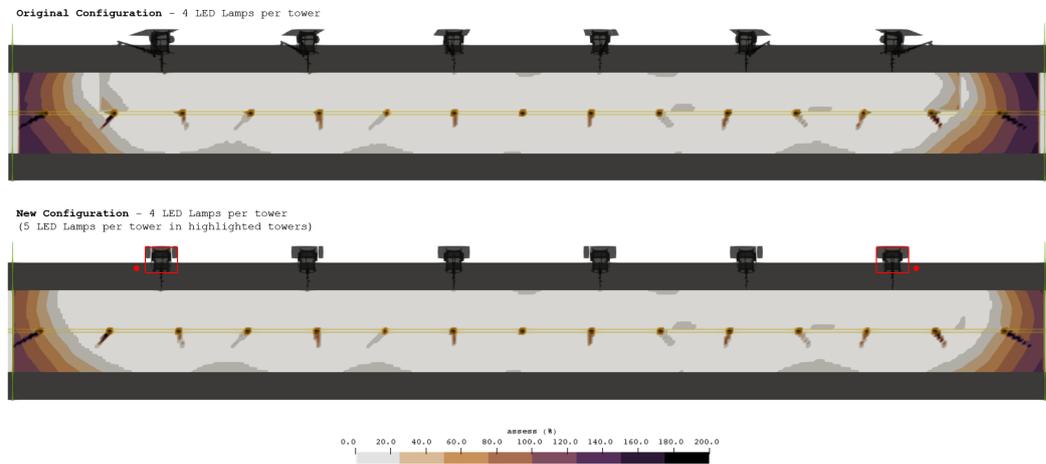


Fig. 3.33.: Relative difference between solar-powered light towers (using LED lamps) and minimum requirement grid. Top: original configuration. Bottom: new configuration.

3.6 Results

The results of both case studies were presented to an architect and various lighting design experts who provided feedback regarding the usability and improvement of our system. Experts pointed out the need to include more metrics for the evaluation of lighting alternatives. For instance, unified glare rating (UGR), color rendering index (CRI), and task priority, among others. This aspect was addressed by facilitating the inclusion of custom-metrics based on single or multiple values. For example, the combination of the weighted difference technique with a multi-layer requirements grid can be applied to compute and evaluate more complex metrics.

The use of *viPhos* in two different domains demonstrated the flexibility of the system as well as the capability to extend its functionalities to fit several applications. Additional experts' feedback suggests that our system is suitable for the evaluation of more complex lighting designs based on approaches such as Human-Centric-Lighting (HCL) [27] and task-tuning [28] where a flexible (dimmable) luminaires array for a particular area is dynamically adjusted to satisfy the needs of multiple types of task.

In contrast to currently available software for the simulation and analysis of lighting alternatives, *viPhos* provides extensive capabilities for the quantitative local analysis

of sub-regions within a modeled scenario. This significantly improves the state of the art since it favors the identification and correction of drawbacks of a lighting design.

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D. Fernandez-Prieto and H. Hagen. Visualization and Analysis of Lighting Design Alternatives in Simulation Software. *Applied Mechanics and Materials*, 869:212-225, 2017.

K. Häb, S. Schweitzer, D. Fernandez-Prieto, E. Hagen, D. Engel, M. Böttinger, and I. Scheler. Visualization of Building Performance Simulation Results: State-of-the-Art and Future Directions. *Visualization Symposium (PacificVis), 2014 IEEE Pacific*, 2014.

Articles to be submitted:

D. Fernandez-Prieto, B. Ravani, and H. Hagen. Simulation-based Evaluation of Solar-Powered LED Lighting Alternatives for Road Work Applications. (*Transportation Research Board Annual Meeting*)

D. Fernandez-Prieto, B. Hamann, B. Ravani, and H. Hagen. Towards the Definition of Task-Oriented Metrics for the Analysis of Lighting Simulation in Industrial Environments (*IEEE Transactions in Visualization*).

Analysis of Spatio-Temporal Event Data

The fast spread and growing popularity of mobile and monitoring technologies has led to a significant increase in the amount of spatio-temporal data that is produced every day. This fact has attracted the interest of decision makers in several domains since these technologies have turned devices into sensors of a wide variety of phenomena. As this type of data becomes ever more available, the need to create systems that help decision makers to gain a better understanding of the multiple levels implicit in the spatial and temporal dimensions of this data remains in force.

This chapter presents *STRAD* (Spatio-Temporal Radar), a web-based interactive visualization system that I created for the exploration of spatio-temporal event data. *STRAD* is designed as a visual query interface that provides an intuitive way for the interactive exploration of temporal and spatial patterns inherent in spatio-temporal event data. In contrast to other developments in the same direction, *STRAD* offers a multilevel exploration approach (both in the spatial and temporal dimensions) that allows to keep the context of the data while querying it. In addition, *STRAD Wheel*, a web-based library that includes the visualization and interactive exploration capabilities of the temporal dimension was derived as a sub-product of *STRAD* and is currently distributed as an open source JavaScript library under a MIT license for its use within other application domains. The following subsections provide a detailed description of the components of the system and its functionalities. Furthermore, two case studies applied to the analysis of event data in the domain of urban planning and one proof of concept demonstrating the use of *STRAD* for the study of manufacturing process control are presented.

4.1 Spatio-Temporal Event Data

The analysis of spatio-temporal event data is an important problem to many application domains. For instance, in a production line, a spatio-temporal event could represent the time at which a particular machine in a manufacturing facility triggered a malfunction or maintenance alarm. In this example, the event contains information about the when (timestamp), where (location/machine), and what (attribute: event type) did happen to the production line at a specific moment in time. While purely spatial data provides information about where an event happened, temporal data provides information about when did an event happen. In addition, the attribute

component provides semantic information about what happened (the nature of the event). Thus, spatio-temporal event data refers to data which contain these components: what, where, and when [77].

Spatio-temporal phenomena occur at several spatial and temporal levels. On the spatial level, the scale of spatial analysis is determined by the size of the units in which the measurements are aggregated. On the temporal level, the time granularities can be aggregated or disaggregated into larger or smaller conceptual units [6]. Although a great portion of the research on spatio-temporal data analysis and visualization has been focused on geographical data, other application domains also consider the spatial component in smaller scales (e.g., team sports analysis: [44], manufacturing: [24, 63], etc.).

The thorough analysis of spatio-temporal events can reveal important behaviors and patterns that might lead to the identification of anomalies or aspects to improve within a system. Interactive visualization tools are well suited to support this analysis since they facilitate the generation and testing of hypothesis. In turn, this promotes better informed and efficient decision-making processes.

4.2 Research Goals and My Contribution

The goal of this project is the development of a web-based system and library that provides visualization support for the interactive query of spatio-temporal event data from a multilevel perspective. My contribution to the enhancement of visualization support for DSS is an interactive visual query interface, which enables decision makers to explore and analyze the spatial and temporal distribution of simulated or non-simulated events preserving the overall context of the data. Additionally, the distribution of the part of the system as an open source library encourages researchers and experts from different application domains to integrate the tool for the analysis of their data. Likewise, as the tool is accessible to a larger audience, this also triggers its continuous development.

With *STRAD*, I improve upon prior work with respect to the integration of the query definition process with the visualization of query result sets. Since temporal and spatial features are common in several application domains (e.g., production monitoring and quality control in manufacturing, climate simulation data, building performance simulation, etc.), *STRAD* can be easily adapted to satisfy requirements of other domains.

4.3 The *STRAD* DSS

4.3.1 Overview

STRAD DSS is a Decision Support System that enables the exploration and analysis of spatial and temporal characteristics of event data. Its design suggests a top-down approach for the exploration of data (from overview to details-on-demand) [95]. First, analysts get an initial overview of the complete data set. Then, analysts can select subsets of the data based on the high-level information displayed in the overview. Once a high level subset is selected, lower-level data associated with the first selections is shown. In a next step, analysts can refine their previous selections as they progress on their analysis. Following, the design decisions, system architecture, as well as use cases in different application domains are described in detail.

4.3.2 Related Work

The exploration and analysis of spatio-temporal data is subject of extensive research in several disciplines such as monitoring of production facilities, urban planning, disaster prevention and management, transportation planning, and epidemiology among others. Much research in recent years has focused on the application of different visualization and interaction techniques with the purpose of providing experts with intuitive means for the completion of their analysis tasks. This research builds on the previous work from two fields that seek to improve the way experts obtain knowledge from the data: Visual Query Systems (VQS) and Visual Exploration Systems (VES). Both approaches are relevant to the design of *STRAD* since they tackle the data exploration problem from different perspectives. Here, a brief description of previous work in these fields that focuses on the analysis of the spatial and temporal characteristics of the data is presented.

On one hand, VQS focus on how to easily define subsets of data that have certain known characteristics. These systems have been traditionally used to support database exploration [21]; they apply the concept of dynamic query controls [1] with the purpose of offering a more intuitive visual environment for the formulation of database queries. In the context of spatio-temporal data, VQS have been mostly used for that purpose. For example, Brewer et al. [18] introduce a collaborative geovisualization environment for the exploration of climate data. In their application, temporal constraints can be configured through interaction with a radial or linear date selection widget. The results of the query are then displayed in a map view. Similarly, Edsall and Peuquet [36] propose a radial time selection widget for the introduction of time-based queries into Geographical Information Systems (GIS). Cavalcanti et al. [22] propose a VQS for spatio-temporal data called S-TVQE.

This system integrates the formulation of spatial and temporal constraints in an integrated environment.

Even though these approaches provide a more intuitive way to define constraints, the visual query interface and the visualization of results are treated independently. This makes it difficult to draw relations between the query parameters and the results. An alternative to overcome this problem has been presented by Draper et al. [34]. In their paper, they describe a visual query interface to simplify the task of identifying correlations among the entities in a relational model. The interface which is organized based on a radial layout, displays all available entities as ring segments. By dragging a particular entity to the interior of the ring (selection), the relations among the selected entity and all the other entities in the model become visible as links. Although this example does not involve the query of spatio-temporal data sets, the guiding principles for integrating the visualization of result sets into the query interface are well illustrated.

On the other hand, VES aim at providing interactive means to explore unknown characteristics of the data. Within this group the most common used techniques include multiple coordinated views in combination with linking and brushing. Robinson et al. [89] present STempo, a system for the exploration and analysis of patterns in spatio-temporal event data. STempo consists of five coordinated views displaying the spatial, temporal, and thematic attributes of events reported in online news articles. Interaction across the views is facilitated through the use of linked selections and highlighting techniques. MacEachren et al. [64] introduce SensePlace2, a web-based system that supports situational awareness in crisis management from the analysis of social media events (Twitter). Multiple coordinated views are also used to explore the spatial, temporal, and semantic content of Twitter events (tweets). Here, spatial selections can be done by clicking on map regions, while time selections can be performed through a timeline display control that encodes the tweet events density over time. Andrienko and Andrienko [5] propose a tool to analyze the spatial distribution of temporal behaviors. They use multiple coordinated views to display the spatial and temporal attributes of the data separately, but in addition, they provide a combined view where both attributes can be displayed in a single visualization.

In the examples mentioned above, either the exploration of time or space are addressed from a multilevel perspective. *STRAD* focuses on the integration of the properties of visual query systems and visual exploration systems with the purpose of facilitating the intuitive exploration of spatio-temporal event data within multiple spatial scales (analysis of events in the whole region of study, per sub-regions, and details inside the sub-regions) and multiple temporal resolutions (analysis of events per year, month, day of the week, and time of the day).

4.3.3 Analysis Workflow

To design a visualization system that helps to uncover spatial and temporal patterns, it is necessary to understand the basic steps within a decision-making process that involves this type of analysis. Zhong et al. [126] described a general purpose workflow for the analysis of spatio-temporal data. This workflow consists of three steps:

1. *Spatio-temporal data acquisition.* Depending on the nature of the phenomenon this process might involve different data acquisition technologies (e.g., user-generated content such as in location-based social networks, GPS data, 3D measurements from Coordinate Measurement Machines (CMM), etc.).
2. *Information modeling of spatio-temporal data.* This step involves the transformation of the raw data into understandable information that reveals interesting patterns within the data. Therefore, this step implies data pre-processing; definition of data storage and query strategies; data filtering, clustering, and pattern detection; adding semantics and knowledge to the data (providing a thematic context to the data); building a conceptual model for the data items; and performing the spatial analysis according to specific-domain tasks.
3. *Visualization.* Selecting the appropriate visualization and interaction techniques that facilitate the detection of patterns, identifying relations between data components, and making inferences. Commonly used techniques for this type of data include maps, histograms, time lines, small multiples (juxtaposed views), aggregated views, and multiple coordinated views supporting brushing and linking interactions among others. An extensive survey of visualization techniques applicable to spatio-temporal data can be found in [2].

4.3.4 Visualization and Interaction Requirements

One of the main challenges in the development of such systems is to keep aligned tasks and requirements along the entire process. There are numerous approaches whose aim is to help researchers and developers in the achievement of this goal. The user-centered design methodology presented in Chapter 2 was applied for the collection of the system requirements.

Questionnaires and unstructured interviews with experts from different application domains were conducted with the purpose to understand and extract the requirements that a system for the analysis of this type of data must fulfill. Among the visualization and interaction requirements there are:

- [R1] *Provide data overview*: visualize a summary of the whole data set prior to exploration. This is especially important to support discover, explore, and summarize actions.
- [R2] *Include focus and context approach*: while exploring specific subsets of the data show an overview of the surrounding information. Discover and explore actions can benefit from using this approach.
- [R3] *Provide interactive means to query the data*: being able to narrow down the data displayed eases the accomplishment of all the actions.
- [R4] *Use of multiple coordinated views to emphasize on different data dimensions*: by having dedicated views for complex data dimensions such as space and time, experts can focus on filtering based on particular characteristics of the data.
- [R5] *Facilitate the visual comparison of temporal and spatial attributes of the data*: incorporate explicit visual strategies for the comparison of different subsets of the data. This requirement is essential in decision making processes.
- [R6] *Use of visual idioms known in the domains*: this property contributes to the learnability of the system (also known as the usability of the system over time).

Additionally, through the unstructured interviews, other requirements which are not directly related to the data but to the system itself were identified. These requirements are:

- [R7] *Portability of the system*: the system can be accessed and used in different environments. Additionally, no special hardware or software is required.
- [R8] *Interactive response times*: to avoid the interruption of the analysis workflow, the system should respond promptly to user interaction.
- [R9] *Ease of update and extension*: updates to the system should be easily accessible by the users. Similarly, the integration of new functionalities should be feasible in a reasonable amount of time.

4.3.5 Implementation

Visual Design

Based on the requirements mentioned above, a visual design for the interactive exploration and analysis of spatio-temporal data was defined. Two coordinated views constitute *STRAD* interface: temporal view, and spatial view. While the temporal view gives detailed information about the registered events at different time resolutions, the spatial view gives domain-specific context to the event data (e.g., factory layout view in the case of material flow data in manufacturing applications, or geographical

view in the case of urban planning related applications). Later, this data is aggregated at different temporal and spatial levels to facilitate the identification of trends and spatial distribution of the events. We follow the visual information seeking mantra proposed by Schneiderman [95]: “Overview first, zoom and filter, then details on demand” to facilitate the multilevel exploration in both the spatial and temporal views. In the following, the visual and interaction principles applied in each view are explained in detail.

Temporal View

The temporal view (later referred to as *STRAD Wheel*) is based on a radial layout due to their suitability to represent the periodic nature of time, in addition to their intuitive and compact way to present temporal sequences. Moreover, studies exploring the properties of radial layouts have demonstrated that the reading direction effect, which impacts the order in which a visualization is read by users (e.g., left-to-right readers), is reduced when using such layouts [32]. Four concentric rings compose the radial visualization of this view. Inside out, the first ring depicts the evolution of events on hourly basis; the second ring acts as an interactive control to select time ranges at the first ring level; the third ring depicts the evolution of events over time on monthly, weekly, and daily basis; and the fourth ring is an interactive control to specify time ranges at the third ring level. Below a detailed description of each ring is given in the same order. Figures 4.1 and 4.2 illustrate the visual elements incorporated in each ring.

- *First Ring: Daily View.* The *first ring* is divided into 24 axes, representing the hours of a day. This particular representation is easily interpreted by users since it can be associated to the lecture of an analog clock. Hourly activity is visualized by piece-wise linear connected line segments provided by histogram data. The dark blue line depicts the total number of events per hour. Diurnal and nocturnal activity can be easily differentiated as a result of the ordering of the axes. Diurnal activity (6 a.m. to 6 p.m.) is located in the upper half of the visualization, and nocturnal activity (6 p.m. to 6 a.m.) is located in the lower half.
- *Second Ring: Time Range Selection.* The *second ring* enables the selection of sequential time periods on hourly basis via a radial range slider. By changing the opening angle, it is possible to adjust the selection of the segment of the year, which is then aggregated and displayed throughout the temporal and spatial view. For example, a selection can be based on the need to explore in detail the events occurring during day or night hours.
- *Third Ring: Yearly View.* The *third ring* is divided into twelve segments representing the months of the year. Each of these segments resembles a cumulative histogram where the sum of the events reported per Day Of the Week (DOW)

is displayed. DOW activity can be segmented by clicking on the buttons located at the bottom part of each segment. Then, hourly activity corresponding to the selected DOWs is visualized in the *first ring*. Similarly, daily activity can be examined by rolling over the points positioned in the axes. A label showing the exact number of events registered during a particular day will pop-up. In addition, a line depicting the total number of events in a month (dark blue line) is plotted with the purpose to ease the comparison on events occurrence among different months of the year.

- *Fourth Ring: Time Range Selection.* Analogously to the second ring, the fourth ring enables the selection of sequential time periods but on monthly, weekly or daily basis. Thereby, it is possible to define a particular period of interest by looking at the data overview provided in the cumulative histogram visualization from the third ring. For instance, a time range selection can be based on the visual identification of a peak in the cumulative histogram visualization.

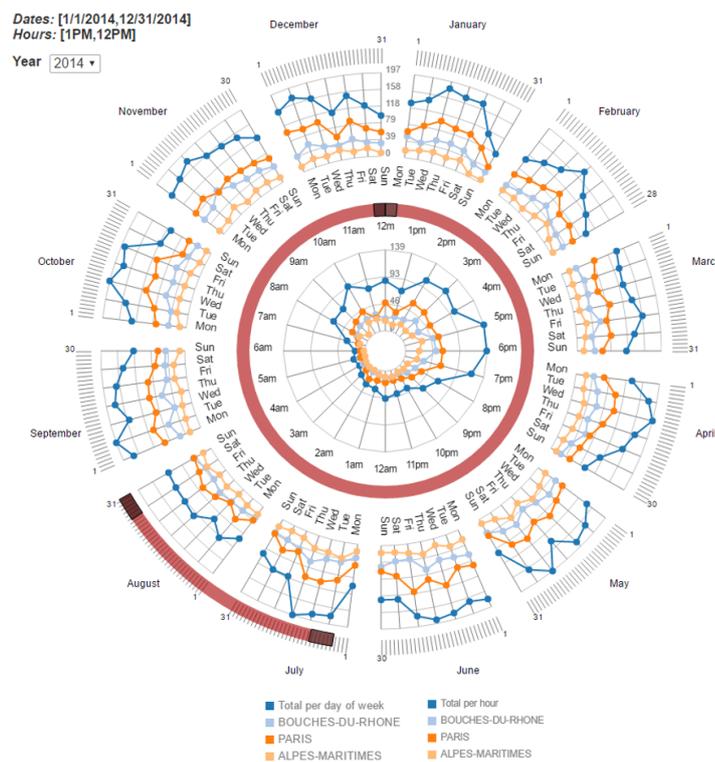


Fig. 4.1.: STRAD Wheel visualization of one year of road accidents in France. The plot lines represent the distribution of events in three different regions. A summary plot line (dark blue) indicates the overall sum of events in the studied regions.

Spatial View

The visual design of the spatial view highly depends on the application domain

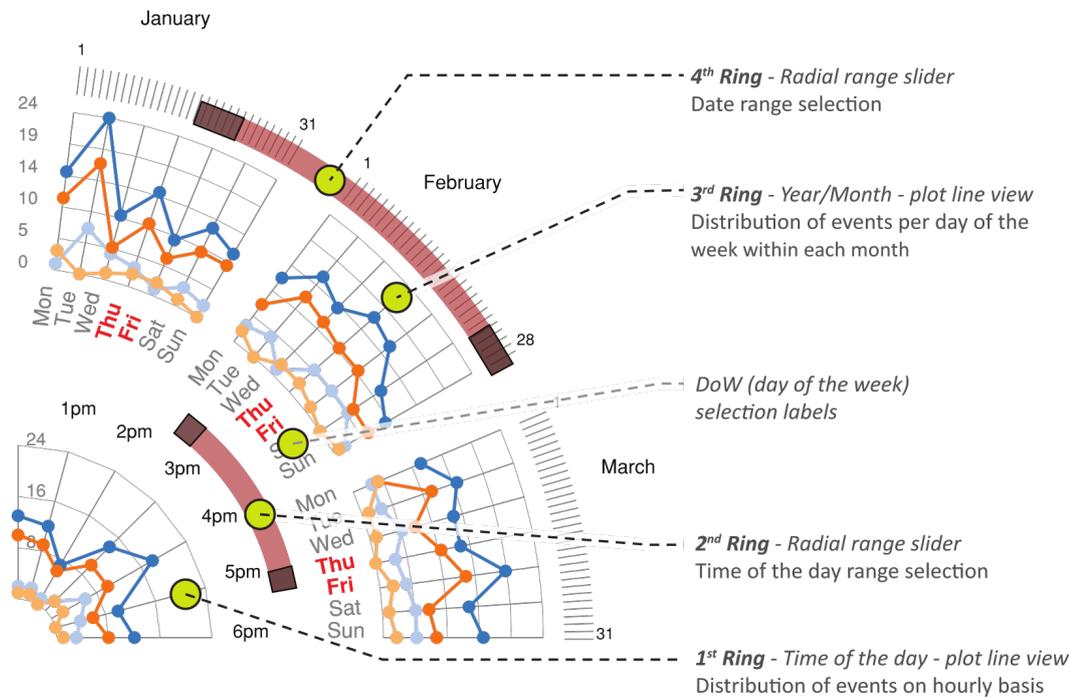


Fig. 4.2.: Close-up of the temporal view. The highlighted day of the week (DoW) indicates that the data displayed in the first ring corresponds to the distribution of events on Thursdays and Fridays.

and the type of spatial data available for the analysis. Below, the visual design of a spatial view specified for the analysis of geographical data is discussed. The spatial view visualizes the geographical distribution of events at two different spatial levels: overall territory and inside regions. By linking the temporal and spatial views, it is possible to select a specific region or a set of regions for which the temporal distribution of the events are to be analyzed. For example, clicking on one region will filter out the events that did not take place in that location. The temporal view will be updated accordingly to display the new subset of events under analysis. When a region is selected in the spatial view, a new **detailed** view is triggered. This view displays the exact location of single events inside the region, providing a better look to the internal distribution of the events. Clicking on two or more regions will not only trigger the detailed view but also the comparative mode. Once two or more regions are selected in the spatial view, new plot lines appear in the temporal view to indicate the particular temporal distribution of events in each selected region (see Figures 4.1 and 4.2).

Figure 4.3 shows an overview of the integration of both views for the analysis of geographical spatio-temporal events. In the figure, the following visualization and interaction components are depicted: a) label indicating the current time interval selected and combobox for the selection of the year. Inside out the temporal view contains: b) 1st ring, displaying the distribution of events per time of the day; c) 2nd ring, interactive control to define time intervals with respect to the times of

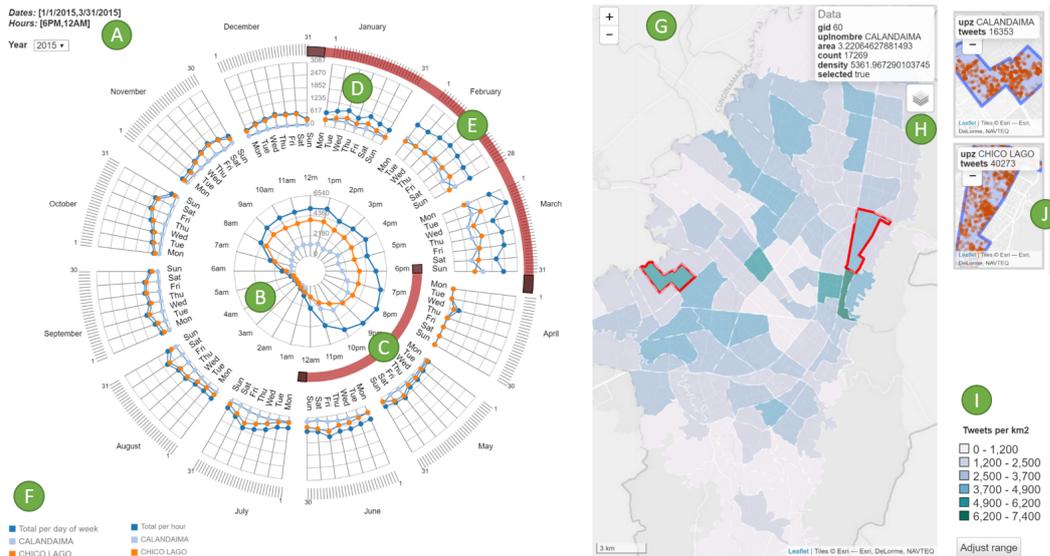


Fig. 4.3.: STRAD's interface showing the visualization and interaction components.

the day; d) 3rd ring, showing the distribution of events per day of the week for every month of the year; and e) 4th ring, interactive control for the selection of time interval within days of the year; f) is the legend that describes the color coding for the selected regions (geopolygons) within the spatial view. On the right side of the picture, the spatial view contains: g) the map view where the domain-specific density metric is encoded as a choropleth map. The selected regions (geopolygons) are marked with a red outline; h) the menu for switching among alternative map representations; i) the legend describing the ranges used for color coding and the button that allows the interactive adjustment of the color scale; and j) the detailed view of the regions in the selection showing the exact location of events inside each region.

System Architecture

STRAD has been implemented as a web application in order to favor mainly three quality attributes: portability, by supporting access to the system from multiple platforms; scalability, by enabling different server configurations in the back-end; and maintainability of the software, by considering a suitable Separation of Concerns (SoC). STRAD's architecture separates the concerns of data processing in the server side (back-end), while the concern of data presentation is managed in the web browser (front-end). Below, we describe the components comprised in the back-end and front-end of our system.

Back-end

The back-end consists of two parts: a database and a web server. A PostgreSQL database is used to store the spatio-temporal event data. The PostGIS module is

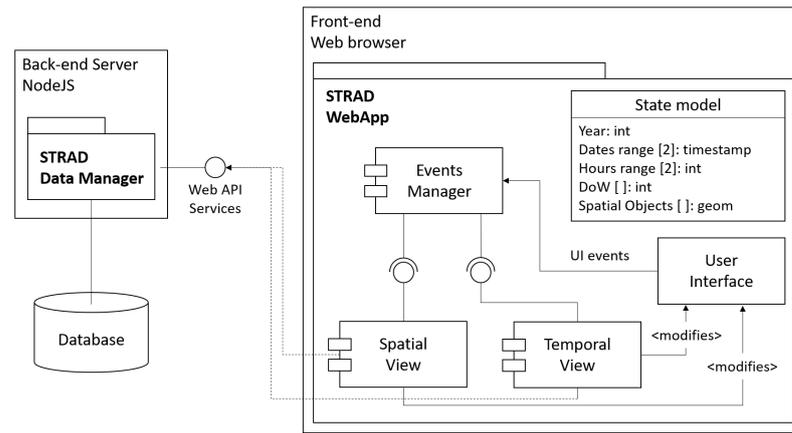


Fig. 4.4.: STRAD system architecture. Components included in the back-end (server side) and front-end (visual query interface).

included to perform spatial operations such as intersections, unions, and distance measurements among others. The server side was implemented using NodeJS (<https://nodejs.org/>) to improve the software’s maintainability since both back-end and front-end are developed in JavaScript language. The server offers a web API based on REST architectural style whereby the processing and extraction of the spatio-temporal event data is facilitated.

Front-end

The front-end follows a Single Page Application (SPA) oriented architecture, which means that a web page is not reloaded during its usage, instead, only the elements of the interface affected by user’s interaction are redrawn. In this case, either the web application makes new calls to update the data, or it changes the presentation based on the current available data. The SPA approach supports rich interaction, leading to a more natural and native-like experience to the user. The components included in the SPA are shown in Figure 4.4.

State Model Component: The state model is used to display changes in the visual query interface. In *STRAD*, it is defined as the list of filters to be manipulated by the users during the visual exploration tasks. These filters are:

- **Year:** represented as an integer and manipulated with a single combobox in the visual query interface. It is the only filter in the state model that has an impact over all components.
- **Dates range:** represented as a fixed array of timestamps of size 2 containing the start and end dates.
- **Hours range:** represented as a fixed array of integers of size 2 containing the start and end times of the day.

- DOW array: represented as an array of maximum 7 elements to filter by the days of the week.
- Spatial Objects array: an array of integers with the IDs of the selected objects within the spatial view.

Event Manager Component: This component is in charge of listening to the events triggered by user interaction in the visual query interface (e.g., HTML-DOM for web applications). Once an event is triggered, this component evaluates the changes in the corresponding objects in the state-model, and delegates the necessary updates to the corresponding views. Consistent with the design of the visual query interface, the temporal and spatial views are associated to their own component in the architecture. These components are deployed as JavaScript files and have the capability of modifying sections in the visual query interface.

Temporal View Component: The temporal view component contains two sub-components each of them defined based on three characteristics: the distinction of the displayed information, the filters associated to their graphical representation, and the filters used to update their own data. These sub-components include:

- Year sub-component: showing the events data per DOW along the months of a year. It is updated when changes in the year, hours-range, or spatial objects array of the state-model are performed.
- Day sub-component: showing the events data per time of the day. It is updated when changes in the year, dates-range, DOW-array, or spatial objects array of the state-model are performed.

Spatial View Component: Likewise the temporal view component, the spatial view component consists of two sub-components defined based on the same three characteristics. In the example presenting geographical spatio-temporal events, the following sub-components are distinguished:

- Choropleth Map: showing the domain-specific density metric for every polygon in the map. This sub-component is updated when changes in the year, dates-range, hours-range, or DOW-array of the state-model are performed.
- Single-events Map: showing single events distributed over all the geographical area of study. It is updated by the same events as the choropleth map but has no impact in any other filter of the state-model. This sub-component uses plugins provided by LeafletJS (<http://leafletjs.com/>) to visualize the events data using alternative visual representations (e.g., heatmap and clusters view).

STRAD Wheel Application Programming Interface (API)

The temporal view of the system (*STRAD Wheel*) is available as an independent web-based library for its use within different applications. The library focuses on the visualization and interactive query of temporal data in a compact view with multiple temporal levels. *STRAD Wheel* is based on D3.js and two additional JavaScript libraries radar.js (<https://goo.gl/zSD441>) and circularbrush.js (<https://goo.gl/aYSf3T>) which were adapted to support the visual and interaction design.

Based on the different graphic components included in the visual design of this view and their functionalities, two types of components were implemented: filters and data representation.

Filters

Related to the selection capabilities included in the *STRAD Wheel* design (second and fourth ring, and DoW labels), four filters were implemented (see Table 4.1).

<i>selected_year</i>	Integer that indicates the year of analysis.
<i>dates_range</i>	Array of size 2 with the initial and final date taken from the selected range of the fourth ring.
<i>dows</i>	Array of minimum size of 0 and maximum of 7 with the selected days of the week.
<i>tod_range</i>	Array of size 2 with the initial and final time of the day taken from the selected range of the second ring.

Tab. 4.1.: Filters available in *STRAD Wheel* library.

Data Representation

With respect to the data that is being represented in the first and third rings two types of plots were identified (see Table 4.2).

<i>year_plotline</i>	Each of the plot lines in the third ring representing data-values per <i>dow</i> of each month. Therefore a <i>year_plotline</i> has $84=12*7$ data-values.
<i>tod_plotline</i>	Each of the plot lines in the first ring representing data-values per time of the day. This means that a <i>tod_plotline</i> has 24 data-values.

Tab. 4.2.: Data representations available in *STRAD Wheel* library.

The *STRAD Wheel* library can be easily used via its Application Programming Interface (API) that provides basic services to manage both, the filters and the data representation components. It provides the getters and setters to access the filters associated to the interactive elements in the tool, it also offers subscription to the events (e.g., `onDatesChange`, `onDowsChange`, etc.) generated by changes on these filters. Regarding the data representation components, the API provides methods to

add, replace or remove plot lines in the first ring (time of the day plot lines) and third ring (values per day of the week for each month).

The source code, API reference as well as a simple example and video demonstrating the usage of the library are available in our GitHub repository at: <https://github.com/cxnvcarol/STRAD-Wheel>.

4.4 Case Studies using *STRAD*

Below, we present two case studies that demonstrate the use of *STRAD* in decision making processes of two different domains (urban planning and transportation planning). First, a brief motivation for the analysis of each data set is presented. Next, the data set and the analysis task are described, followed by the analysis and report of insights gained from the multilevel exploration of the data.

4.4.1 CS1: Twitter Events in Bogotá's Urban Perimeter

Twitter is one of the most popular Location-Based Social Networks nowadays. It is estimated that more than 6000 tweets are generated every second [86], and approximately 20% of them are geotagged [115]. This extensive data source offers urban planners the opportunity to get a better understanding of where are the citizens, what are they doing, and when.

Data

For this case study, a collection of approximately 4.5 million of geotagged tweets within the urban perimeter of Bogotá, Colombia corresponding to the period between October 2014 and January 2016 was used. This data has been gathered using the Twitter Streaming API [113]. According to the documentation, the API provides access to up to 1% of the total firehose volume.

Task

Three experts in urban planning from the city of Bogotá participated in this case study. Their objective was to test the hypothesis that regions with high twitter activity during the night leisure times (usually Fridays and Saturdays between 10pm and 3am) indicate the location of already known night leisure areas. The discovery of new hotspots within this time interval could reveal the origin of new night leisure areas.

Analysis

From the overview, the first thing noticed by the experts was the drastic decrease of SMA from April to October 2015 (see Figure 4.6-left). For this reason, they chose the period with a higher amount of tweets (January to March 2015) for

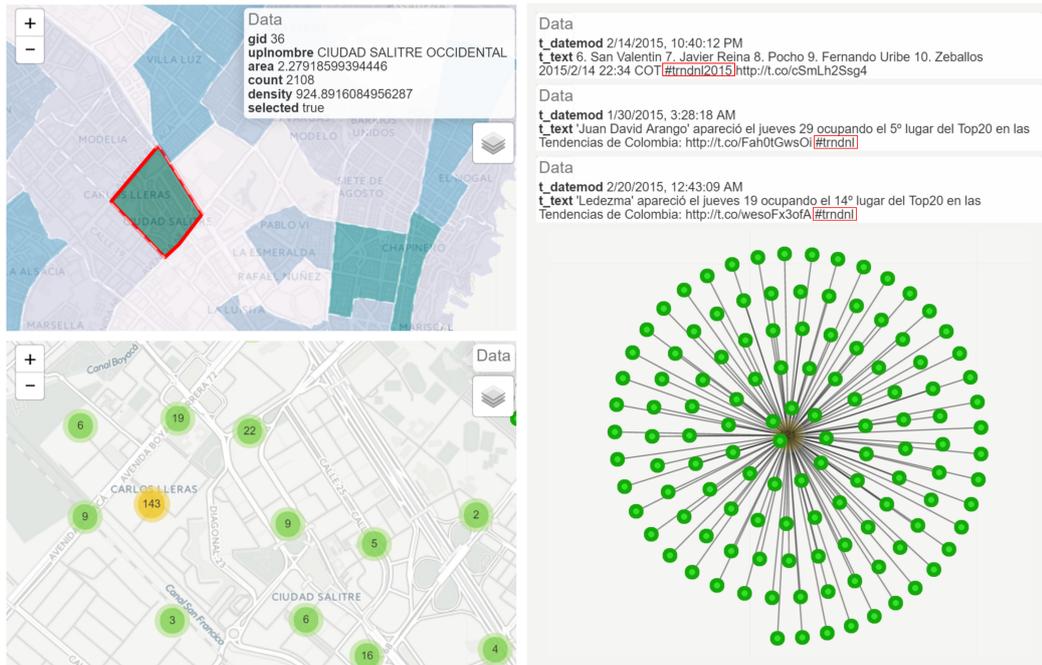


Fig. 4.5.: Identification of false-positive in “Salitre Occidental”. The exploded view on the cluster shows that all the events are generated in a single location. The content of the tweets helped to identify the account that published these tweets (*#trndnl*).

the analysis. In the spatial view, experts detected an unexpected high density in the “Salitre Occidental” region; the clusters view showed a high concentration of events in a single point. The exploded view of the cluster showed that all the events were originated in the same location. After exploring the information of single events (content of the tweet), experts were able to determine that the high concentration of tweets was caused by a single user/account. This account published systematically tweets about the trending topics in Colombia (see Figure 4.5). Experts classified this region as a false-positive in the context of this task. Excluding the false-positive, further exploration of the other regions helped experts to validate their hypothesis. The regions showing a high density of events ($density = \# events / K^2$) highlighted the night leisure areas most frequented by the citizens of Bogotá. The heatmap and clusters view showed a more accurate location of those hotspots (see Figure 4.6).

4.4.2 CS2: Road Safety in France

According to the 2015 Road Safety Annual Report published by the OECD-ITF (Organisation for Economic Co-operation and Development - International Transport Forum) [72], France experienced an increase of 3.7% of fatalities in 2014 with respect to the previous year. Analysts inferred that the favorable weather conditions –2014 has been the warmest year since 1900– contributed to the increase of road

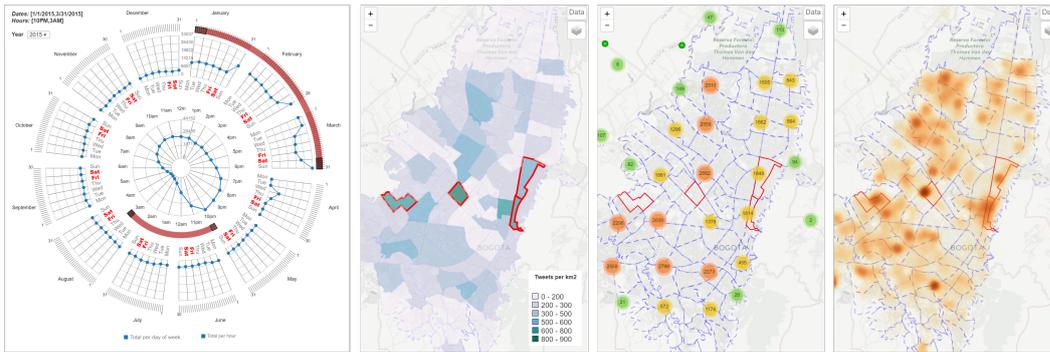


Fig. 4.6.: Identification of hotspots during night leisure times in Bogotá.

trips of French citizens. A deeper exploration of this data can bring insights about where to focus the implementation of additional safety strategies and measures.

Data

For this case study, the French road safety data collection of 2014 was used. The data comes from the BAAC (Bulletins d'Analyse d'Accident Corporel), an archive managed by the French Road Safety Observatory (ONISR) [78]. The data set consists of 57,841 registers of accidents within the European territory France of which only 38.28% have exact geographical coordinates. The remainder registers have partial georeference that corresponds to the department code, commune code, and in some cases the address where the accident happened. For these registers, we used as geographical coordinates the centroid of the commune where the accident was reported in order to take this registers into account for the computation of the density metric.

Task

Two experts in transportation planning participated in this case study. Their objective was to study the accidents distribution during July-August, two of the months with highest traffic in France due to the summer school holidays that usually go from 5. July to 31. August. Afterwards, experts wanted to explore in detail the regions that showed higher densities. Through the analysis of the specific locations of the accidents, experts wanted to map out the most dangerous places or segments of the road network. The density metric defined for this case study ($density = \# events / 100K inhabitants$) serves as a proxy for indicating the risk that an inhabitant gets involved in a traffic accident. Despite a density metric as described in section 3 would have been more meaningful, we did not have access to the vehicles registry information.

Analysis

The first overview of the data already evidenced a higher density in the region of Paris and its surrounding as well as in the Mediterranean coast. As the density in the other regions appeared to be masked, the adjustment of the color scale (setting up

the maximum value in the color scale to *150 accidents/100k inhabitants*) helped to highlight the contrast along all departments of France (see Figure 4.7).

Starting with the analysis of the data in the defined time interval, experts found two major regions that drew their attention: Paris and the departments comprised in the “inner ring” (*petite couronne*), and four departments in southern France which border the Mediterranean coast or Italy. The comparison of the two departments with higher densities (Paris and *Alpes-Maritimes*) revealed a decrease of accidents in August with respect to July in Paris (407 accidents in July and 373 accidents in August) while the department of *Alpes-Maritimes* developed the opposite behavior (143 accidents in July and 151 accidents in August). This could indicate a higher traffic in the southern region of France for the second period of holidays, probably caused by the increase of travelers that visit the Mediterranean coast during summer (See Figure 4.8). Unfortunately, the lack of exact geographical coordinates in these departments made impossible the distinction of routes with high accident rates. Therefore, experts decided to start a new exploration by comparing the temporal and spatial distribution of the four departments within the “inner ring” along the whole year. The comparison of the four departments in the temporal view showed that Paris had highest amount traffic accidents. In most cases, Paris exceeded by more than double the number of accidents of the neighboring departments. In the spatial view, the detailed maps of each region revealed that particularly Paris and *Haut-De-Seine* had a low rate of events with exact geographical coordinates. A gray point in the center of the departments in the detailed view indicated the existence of events with no exact location. A closer look to the raw data map of the other two departments showed a high concentration of accidents in a particular road segment in the south-west area of *Seine-Saint-Denis*. This segment coincided with the *Autoroute A3* that connects the “*Boulevard Périphérique de Paris*” with the *Autoroute A1* that goes to the north of the country (See Figure 4.9).

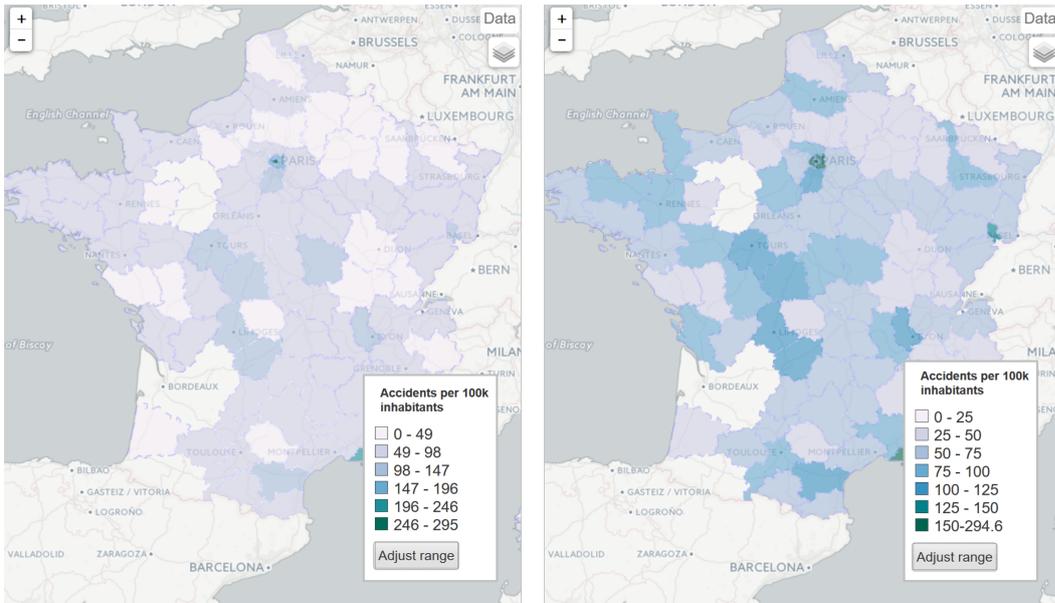


Fig. 4.7.: Interactive adjustment of the color scale in the choropleth map to highlight specific value ranges.

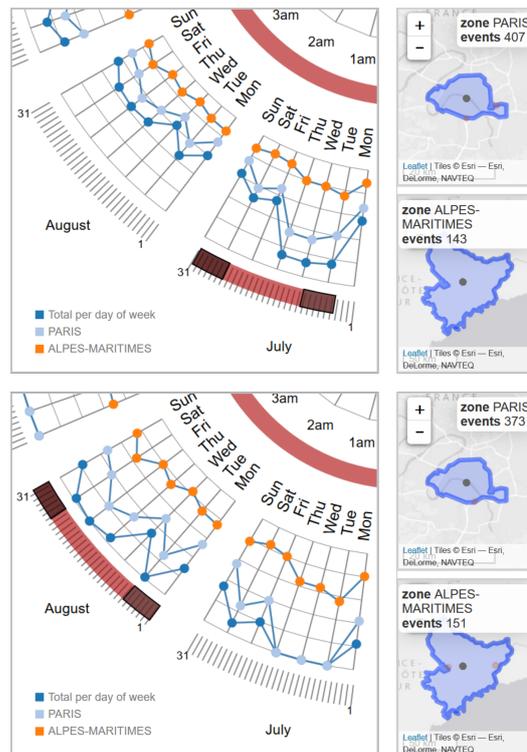


Fig. 4.8.: Spatio-temporal analysis of traffic accidents in two departments of France during the summer holidays period (05.07.2014-31.08.2014).

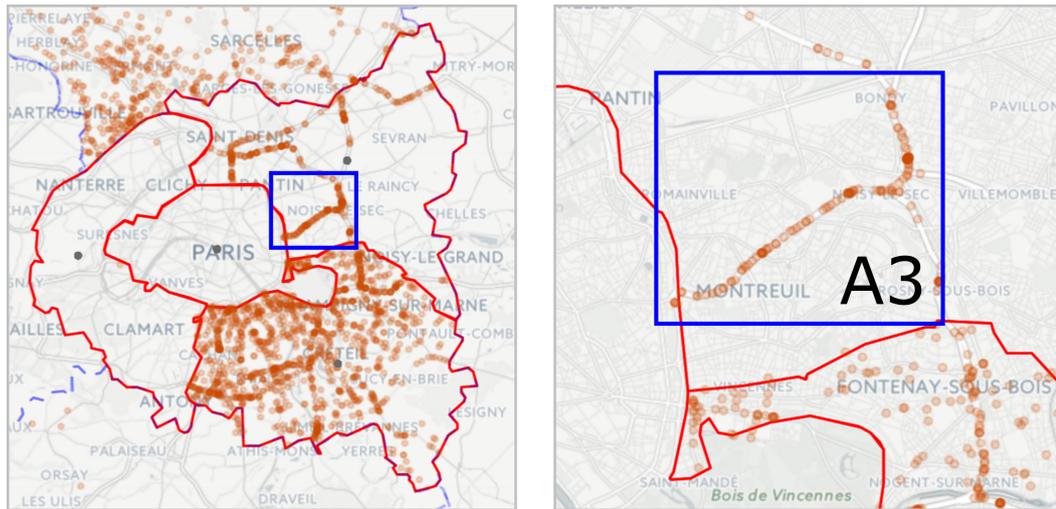


Fig. 4.9.: Detailed view of the raw events map displaying a high concentration of traffic accidents in the Autoroute A3 in Seine-Saint-Denis, France.

4.5 STRAD DSS in Manufacturing Applications

Manufacturing Process Control for Quality Assurance

In manufacturing, quality control is a process that ensures that a system maintains a desired level of quality. This is accomplished by measuring the quality characteristics of resulting products and comparing them with reference measurements (optimal measurements). This process aims at detecting significant deviations among these measurements, thus a correcting action can be applied to restore the targeted quality level. For example, in the automotive industry, one of the numerous processes subject to quality control is sheet metal forming. In this scenario, a measurement plan indicating the position and optimal values of measurements of relevant features on the designed part is created. Next, these features are measured on the produced parts with the assistance of, for example, Coordinate Measurement Machines (CMM) and analysis software. Finally, these measurements are compared to the optimal measurements, which are commonly stored in a computerized geometric model of the part. According to the analysis of these measurements, it is determined if the part should be discarded (defective part), or if it satisfies the quality standards and can be used in further stages of the production.

In this type of scenarios, visualization support for the detailed spatio-temporal exploration and analysis of feature measurements can bring insights on different levels.

- *Efficient identification of defective production batches.* The linked analysis of temporal and feature characteristics can uncover a failure of a specific manufacturing process at a particular time (e.g., a significant percentage of

the produced parts show a large deviation in the measurement of feature “A1”. This can indicate a defect on the machine responsible for the machining of this feature).

- *Historical quality behavior of the system.* The study of the systems and quality control processes over time can serve as a tool for the evaluation of the production. An easy to understand visualization can favor the communication process among stakeholders which are not necessarily familiarized with the details of the quality process. Then, based on this information, decision makers can take the necessary corrective actions.
- *Identification of sensitive regions/processes.* The analysis of the measurements of parts that failed the quality control check can help identifying the main features that determine whether a part is likely to pass or fail the quality control check. Likewise, this analysis can help in the identification of machining processes that have a great impact on the quality of the produced pieces.

With the purpose of demonstrating the applicability of *STRAD*, particularly *STRAD Wheel* in manufacturing process control for quality assurance, a proof of concept presenting the analysis of measurement data from a semi-conductor manufacturing process over the course of one year was prepared.

Data

The data set used for this proof of concept, “SECOM Data Set” (<https://archive.ics.uci.edu/ml/datasets/SECOM>), resembles a quality monitoring procedure in the semi-conductor manufacturing industry. It consists of a collection of 1567 product examples (produced in the course of one year) for which a series of signals/features were measured at different points of the production process. Each example consists of a date-time stamp, 590 features (representing a recorded measurements), and a label that indicates if the example passed or failed a quality check (-1 corresponds to pass and 1 corresponds to fail). The structure of the data is detailed in Table 4.3 and Table 4.4. This data set is available on the UCI Machine Learning Repository [60].

Attribute	Description	Type
id	id of the product example	Quantitative
feature[0...589]	measured feature values	Quantitative

Tab. 4.3.: Description of Table 1 in SECOM data set.

The challenge from the machine learning perspective is to efficiently and effectively identify the most relevant features that help to determine if a part will pass or fail the quality control check. A predictive model can be later developed and trained to classify new parts. In this case, the focus is on the feature selection process for the

Attribute	Description	Type
id	id of the product example	Quantitative
result	label that represents if the product example passed or failed the quality check	Categorical
timestamp	timestamp assigned at the time of the quality check	Continuous

Tab. 4.4.: Description of Table 2 in SECOM data set.

following visual exploration and analysis of the values measured for these features. The approach for the data pre-processing and feature selection algorithm used in this proof of concept are described below.

Data pre-processing. This data set is particularly challenging because it has data quality issues (e.g., null values, missing values, noise, etc.) as it is common in real life data. Besides these issues, the data set is highly unbalanced, which makes it more difficult to perform feature selection. To address these issues and provide a cleaner data for the analysis of feature measurements, Wuest’s pre-processing approach (second approach, variant 2) [123] was applied. In this approach, all product examples containing more than 6% of missing values are removed. This reduces the data set from 1567 product examples to 1209 product examples in which 6.94% do not pass the quality check. Next, features that contain more than 10 missing values are eliminated, resulting in 523 features out from 591. After this process, the pre-processed data set contains 1209 product examples from which 30 product examples still contain missing values. These 30 product examples are then eliminated. Table 4.5 summarizes the before and after pre-processing step for the SECOM data set.

	Original data set	Pre-processed data set
# of product examples	1567 (100%)	1209 (77.15%)
# of features	590 (100%)	523 (88.49%)
Passed/failed ratio	93.36% passed, 6.64% failed	93.06% passed, 6.94% failed

Tab. 4.5.: Before and after the pre-processing step.

The resulting data set preserves the passed/failed ratio with respect to the original data set, therefore no bias has been introduced after the product examples elimination process. Regarding the feature elimination process, the applied elimination criteria (more than 10 missing values) result in a larger (favorable for further feature selection) set of features in contrast to other approaches presented by Wuest [123].

Feature selection. The purpose of feature selection is to obtain a subset of the most relevant features to later consider the causal relationships within these features. For this proof of concept, two algorithms for feature selection were tested: random forest importance from the Fselector package for R [91] and recursive feature elimination from the caret package for R [58]. The algorithm selection was made considering the characteristics of the pre-processed data set. Considering that the data set is highly unbalanced, random forest algorithm was chosen because it applies methods for balancing error for this type of data sets, hence, it can be used to get estimates of variable importance [17]. The recursive feature elimination was also implemented with a random forest model for prediction.

Each algorithm was run 10 times and the results were analyzed in order to select a set of 5 features with the most relevant information. A description of the applied algorithms is presented below.

1. `random.forest.importance (FSelector)` [91]: This function is an extractor for variable importance measures produced by Breiman's random forest algorithm for classification and regression [17]. The random forest algorithm generates multiple unpruned classification trees. At the end, the algorithm chooses the classification with most occurrences in the forest. Each tree is trained with about two thirds of the examples, leaving an oob (out-of-bag) data used to calculate unbiased classification error. When the forest is generated, values of variable n are permuted in the oob cases. The average of the difference between the tree-occurrences for the permuted variable n and the tree-occurrences for the untouched variable n assigns the importance score for the given variable.
2. `rfe (caret)` [58]: This function implements backwards selection of features based on predictor importance ranking considering a prediction model. The model selected for this specific implementation was random forest. Initially, the algorithm calculates a series of variable subsets and generates a model for each. The model performance is quantified and compared with the resultant models for different variable subsets. At the end, the predictors are ranked and the less important ones are eliminated, leaving the ones that produce the most accurate model.

Based on the results of the identification of relevant features, the visual exploration and analysis focus on the discovery of atypical behaviors of these feature measurements over time and their interrelations.

Task

The objective of this exploration is to identify the Region (or regions) of Interest

(ROI) within the SECOM data set. A ROI is defined as a period containing large production of product examples and a high product-example-failure index. The identification of such ROI's can help in determining periods for which changing the production setup or quality assurance process' setup may have a great impact to the production of an entire year. To guide this exploration, a set of tasks were prepared with the help of production engineers as well as visualization experts.

- Identify period with largest production.
- Considering this period:
 - Identify period with largest failure rate.
 - Identify period with smallest failure rate.
- For each identified period, is it possible to relate it to a specific day of the week (dow)? A specific time in the day (hour)?

Analysis

The final data set was visualized using *STRAD Wheel* along with a descriptive view as shown in Figure 4.10. The temporal view presents an overview of the amount of product examples assessed in 2008. The descriptive view presents histograms for each of the selected features. Two-way communication allows filtering information of interest between views.

The temporal view can be populated with the frequencies of product examples (general overview) or with the average of values for each feature through time (single-feature exploration). In both cases, product examples are discriminated according to the result of the quality check (red and green plot lines depicting product examples that failed and passed the quality check, respectively).

The descriptive view presents two histograms per each of the selected features. The left column depicts the distribution feature values for product examples that passed the quality check, and the right column depicts the distribution of feature values for product examples that failed the quality check. To highlight unusual feature values, product example values that lie outside one standard deviation of the product examples that passed the quality check are colored in red while the rest are colored in gray (right column).

By exploring the data on the temporal view, it is possible to identify that August and September comprise over 56.41% of the year's production, making them the busiest months, as shown in Figure 4.11.

Within this time range, two periods were distinguished based on the relationship of pass / fail product examples and the amount of manufactured product examples:

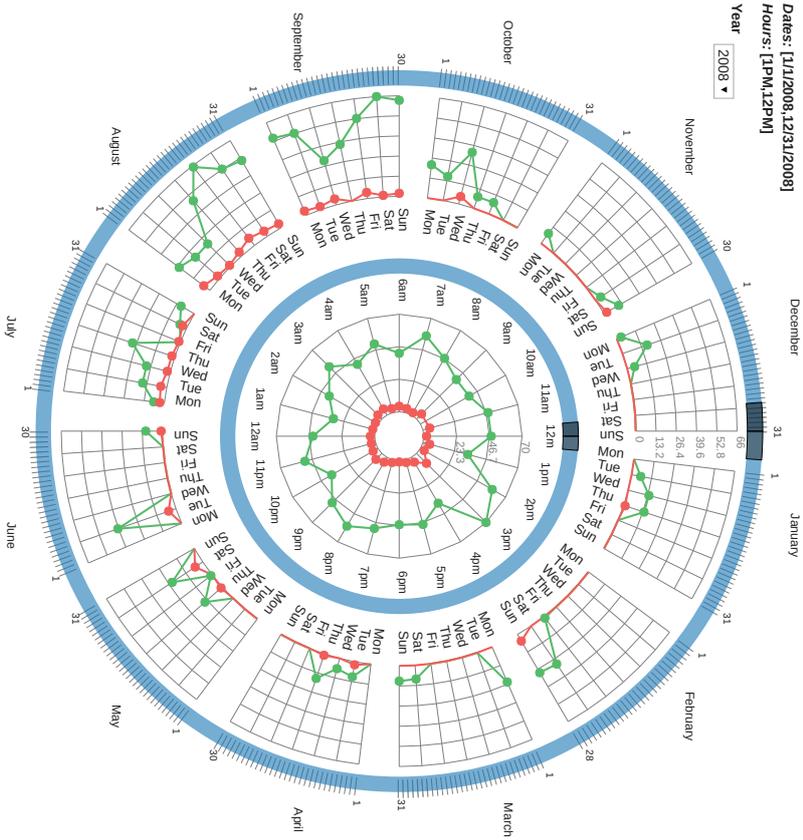
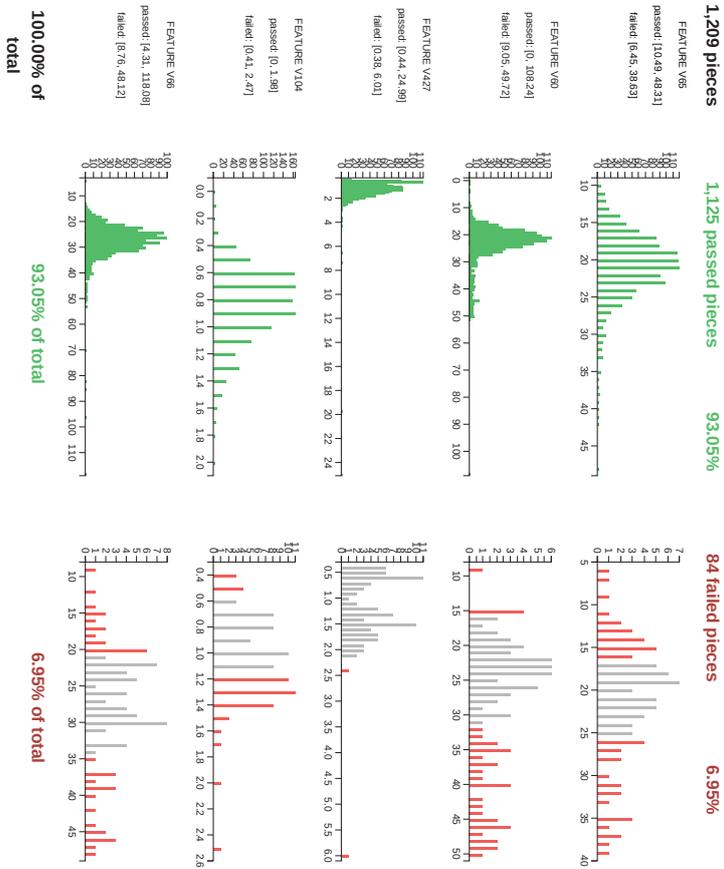


Fig. 4.10.: Overview of the SECOM data set using STRAD wheel.



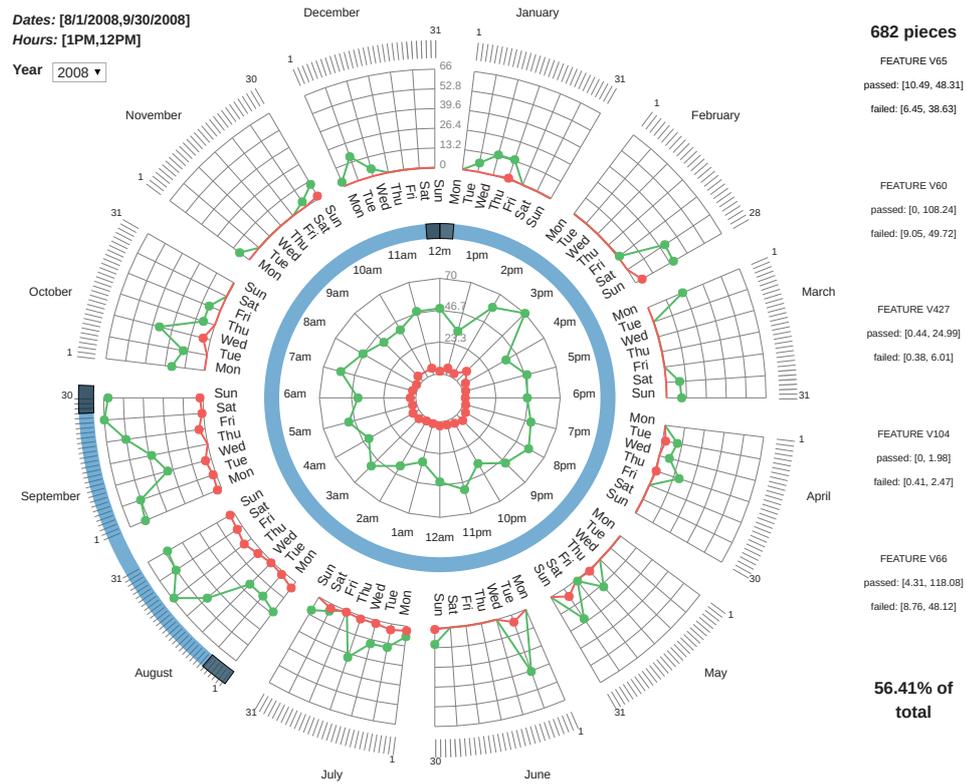


Fig. 4.11.: Exploration of quality check results for the time range with 56.41% of the year's production (August-September).

- Period A: Mondays, Wednesdays and Fridays. Comprises 22.50% of the production between August and September with 8.46% failure rate, as shown in Figure 4.12 (left).
- Period B: Tuesdays, Saturdays and Sundays. Comprises 26.55% of the production between August and September with approximately half of period A's failure rate (4.36%), as shown in Figure 4.12 (right).

For periods A and B, the production behavior varied according to specific times of the day. Figure 4.13 depicts the hour behavior for failed product examples in both periods. For instance, Period B had a constant behavior during the times of the day with an exception at 9 a.m. On the other hand, for Period A, the largest number of failed product examples was between 3 p.m. and 4 a.m.

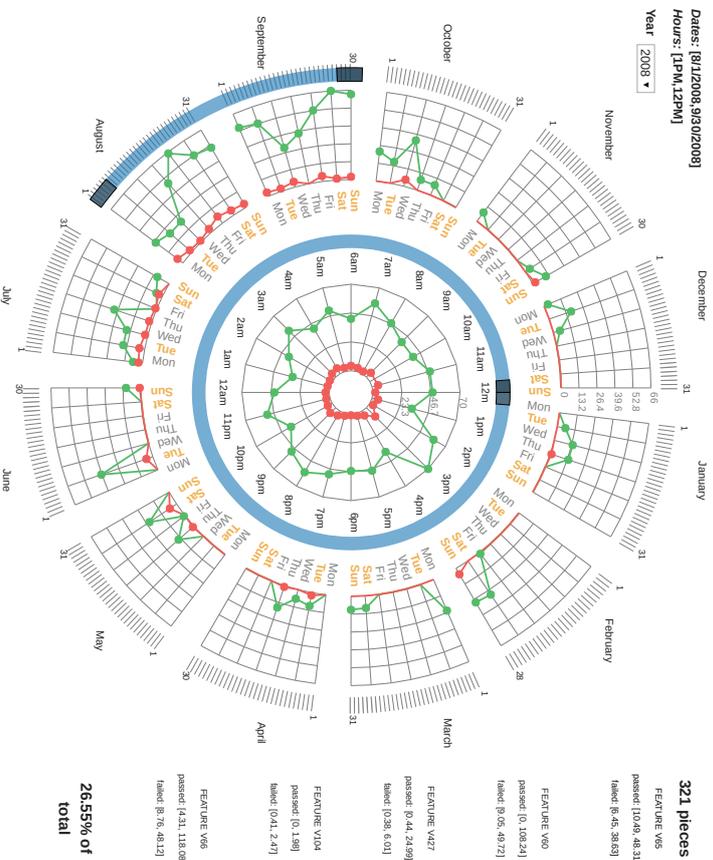
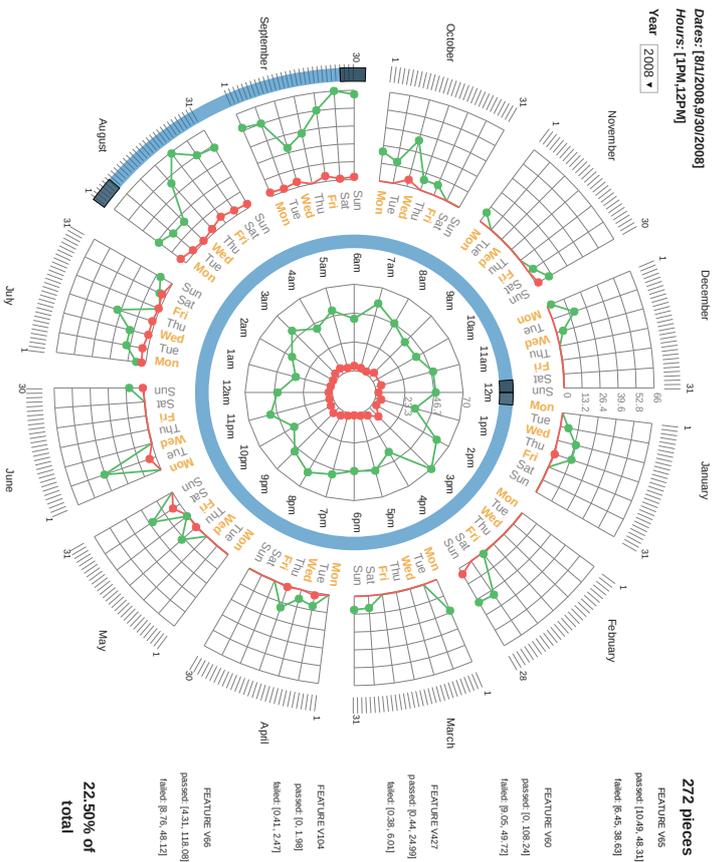


Fig. 4.12: Days of the week with the largest (left) and smallest (right) failure rates between August and September.

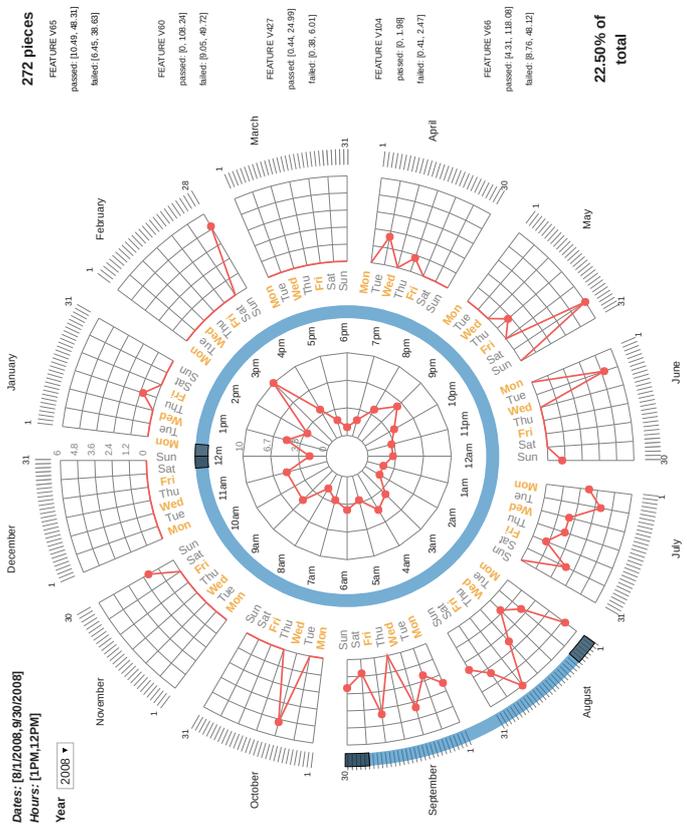
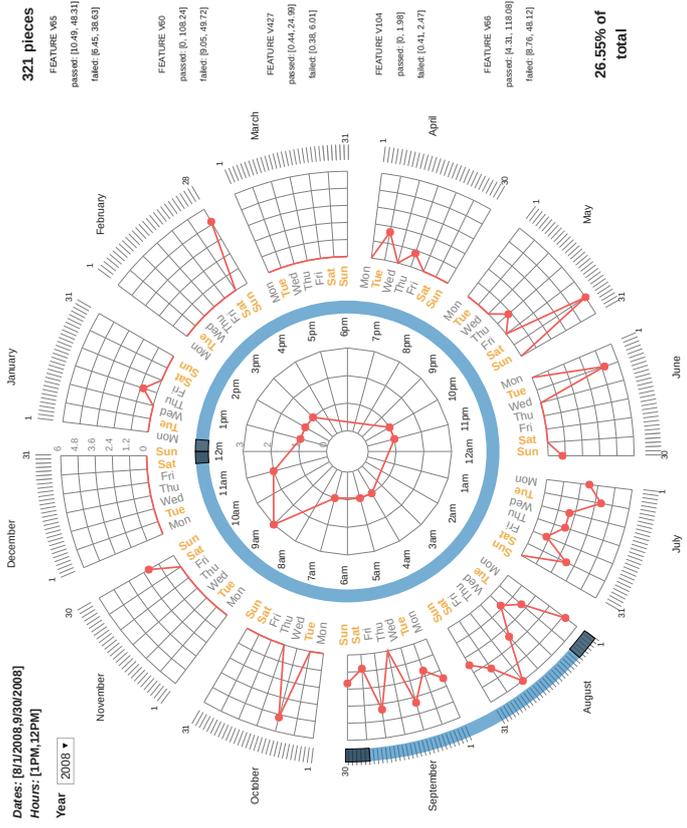


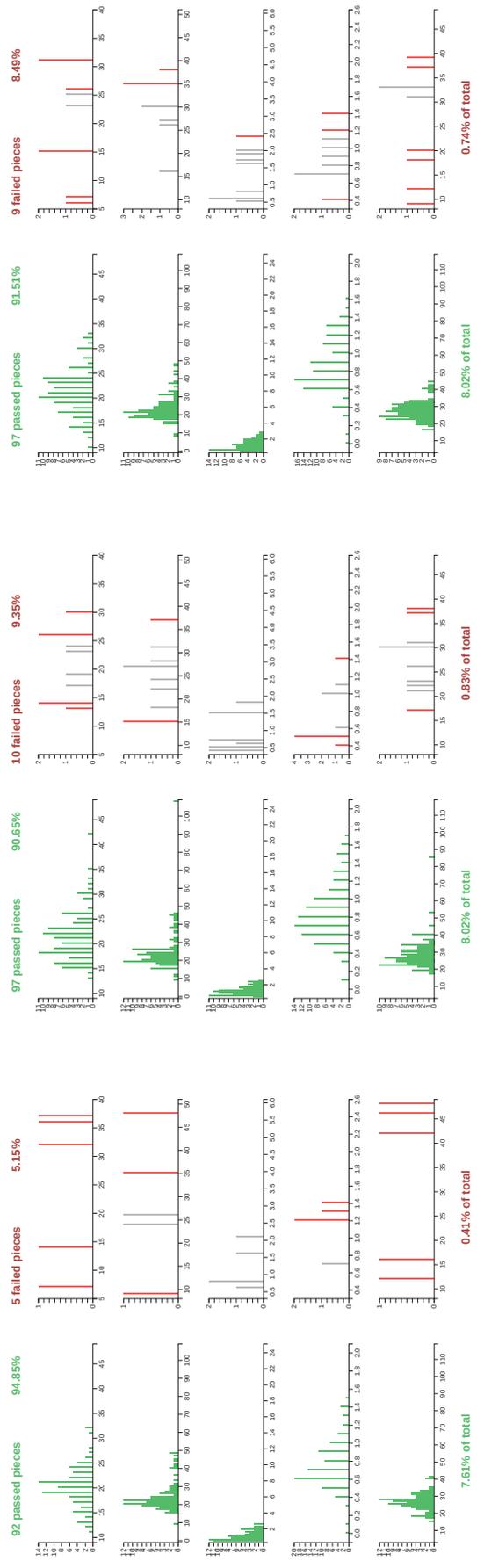
Fig. 4.13.: Time of the day behavior for Period A (left) and Period B (right) for failed product examples.

Based on the previously identified behavior, the analysts made the assumption that each day could be segmented into three shifts: morning shift (from 6 a.m. to 2 p.m.), evening shift (from 2 p.m. to 10 p.m.) and night shift (from 10 p.m. to 6 a.m.). Figures 4.14 and 4.15 show the feature measurements during the three shifts for both periods.

Analyzing the behavior of the production during the three shifts, analysts noticed that Period A had a significantly different behavior among shifts. Particularly, evening and night shifts presented high failure rates (9.35% and 8.49%, respectively) in contrast to the morning shift (5.15%). This behavior might be related to a human mistake (a worker handling a specific machine), the malfunction of one of the machines, a calibration problem during the process of measuring the manufactured product examples, among other possible causes. On other hand, Period B did not have great changes between in failure rates among shifts. However, morning and night shifts had higher failure rates (6.5% and 5.00%, respectively) in contrast to the evening shifts (2.33%).

Focusing the attention on possible causes for the failure rates presented during the evening and night shifts for Period A, and the morning shifts for Period B may provide clues on how to improve the quality of the production. With respect to Period A, approximately 8% of the year's production was produced during the evening and night shifts. About 10% of the product examples produced during these shifts failed the quality check. Regarding Period B, approximately 10% of the year's production was produced during the morning shift and about 6% of the product examples failed the quality check.

In conclusion, the proposed analysis workflow supported by *STRAD* allowed analysts get an overview of the data set and generate initial hypothesis about the behavior of the production quality. A further exploration of these hypotheses helped in the identification of potential Regions of Interest (ROI's) within the data. This proof of concept demonstrated that *STRAD* and *STRAD Wheel* can potentially support manufacturing process control strategies through the direct exploration of the data. Without a doubt, having more information about quality control processes as well as production processes and tolerances for each of the measured features, would significantly benefit the outcome of this type of analysis.



(a) Period A - Morning (b) Period A - Evening (b) Period A - Night

Fig. 4.14.: Time of the day behavior for Period A during morning (a), evening (b) and night (c) shifts.)

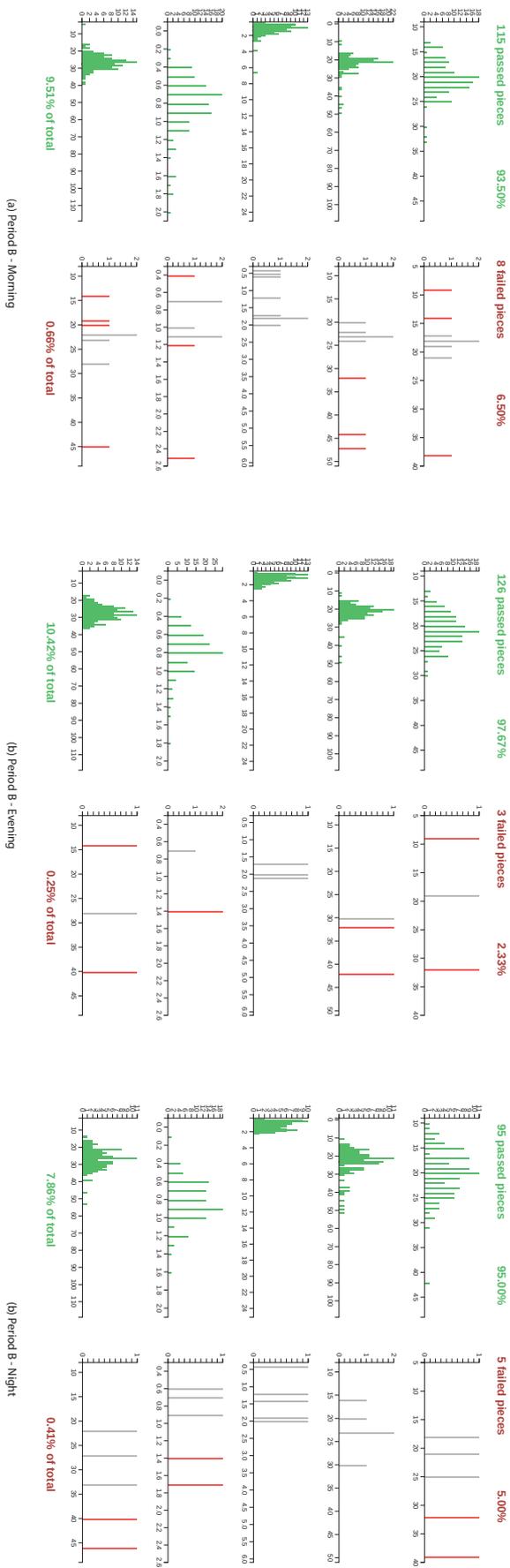


Fig. 4.15.: Time of the day behavior for Period B during morning (a), evening (b) and night (c) shifts.

4.6 Results

STRAD DSS provides an intuitive interface that combines principles addressed by visual query systems and visual exploration systems. This enabled analysts to interactively formulate data queries from a multilevel perspective (e.g., multiple spatial/attribute levels and temporal resolutions implicit in event data).

Analysts from the three application domains successfully generated several hypothesis about the behavior of the studied systems based on the visualized information. Further investigation allowed analysts to prove, disprove, or suggest deeper analysis of these hypothesis. The results obtained in the analysis of the case studies evidenced that *STRAD DSS* and *STRAD Wheel* are powerful tools for the analysis of spatio-temporal and attribute-temporal event data. Thanks to the exploratory nature of the proposed analysis workflow, the system demonstrated to be ideal for initial data explorations.

In particular *STRAD Wheel* library proved to be a versatile tool for the visualization of the temporal distribution of events applicable to different application domains.

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C. Naranjo-Valero, D. Fernandez-Prieto, J. T. Hernández, and H. Hagen. STRAD Wheel: Web-based Library for the Visualization of Temporal Data. *IEEE Vis 2016 Workshop on Visualization in Practice: Open Source Visualization and Visual Analytics Software*, 2016.

D. Fernandez-Prieto, E. Hagen, D. Engel, D. Bayer, J. T. Hernández, C. Garth, and I. Scheler. Visual Exploration of Location-Based Social Networks Data in Urban Planning. *Visualization Symposium (PacificVis), 2015 IEEE Pacific*, 123–127, 2015.

Articles to be submitted:

D. Fernandez-Prieto, M. Vanegas, J. T. Hernandez, H. Hagen, and B. Ravani. Visualization-Based Analysis of Quality Control Measurements in Manufacturing. (*Journal of Manufacturing Systems*)

Conclusion

As the design and operation of manufacturing systems become more complex, the usage of simulation-based tools that help modeling and recreating their operation has gained considerable strength over the last decades. Not only the design of the manufacturing facilities, but also the strategies to monitor their proper operation and the quality of the produced products, are key aspects for the success of modern manufacturing systems. Along with the use of simulation tools, the need to efficiently and effectively understand and communicate their outcome to an interdisciplinary audience is an open challenge.

The systems presented in this dissertation tackle many issues that previously obstructed the seamless and full use of simulation data for decision making in manufacturing. The following sections answers the questions: what can be done now that was not possible before?, and how does this work supports and improves the analysis of the data in the manufacturing domain as well as in the other explored domains?

viPhos

Lighting designers now count with a system that enables the evaluation of a series of standard and custom designed metrics among multiple lighting alternatives. While most of the currently available tools give a great importance to the photorealistic visualization of lighting scenarios (which can be used for qualitative evaluation), *viPhos* provides an accurate and quantitative approach for the global/local comparison and evaluation of lighting distribution.

The analysis and visualization techniques implemented in *viPhos* can be applied for the study of other simulation data that considers the distribution of a physical property within a space (e.g., indoor climate conditions within a manufacturing facility).

Key Features:

1. Fast identification of problematic regions (color mapping)
2. Easy comparison of lighting design alternatives against standards
3. Visual summarization of multiple / similar lighting alternatives
4. Support for global and local analysis of lighting distribution
5. Interactive visual exploration and comparison of simulation results

STRAD DSS

Since temporal and spatial/attribute features are common in several application domains (e.g., climate simulation data, manufacturing process control, building performance simulation results, etc.), *STRAD DSS* can be easily adapted to satisfy the requirements of multiple application domains.

With *STRAD DSS* analysts now count with an easy-to-use and easy-to-access system that favors the visual identification and exploration of spatio-temporal or attribute-temporal patterns within a single visualization.

Key Features:

1. Easy to access web-based platform for the exploration of event data (spatio-temporal and attribute-temporal)
2. Multilevel exploration of events without losing the context of the data
3. Intuitive interface for the visual identification of patterns, ideal for first data explorations
4. Easy creation of data queries via visual query interface
5. Compact and intuitive visualization of temporal data properties

The architecture of the presented systems is flexible enough to facilitate the inclusion of further visualization and analysis techniques. Additionally, a great contribution has been made by distributing *STRAD Wheel* (the temporal view implemented in the system) as an open source library. Thanks to this initiative, *STRAD Wheel* can be freely used and improved in other projects.

Bibliography

- [1] C. Ahlberg, C. Williamson, and B. Shneiderman. Dynamic Queries for Information Exploration: An Implementation and Evaluation. In *Proceedings of the SIGCHI conference on Human factors in computing systems - CHI '92*, pages 619–626, 1992 (cited on page 71).
- [2] W. Aigner, S. Miksch, H. Schumann, and C. Tominski. *Visualization of Time-Oriented Data*, number 1997 in Human-Computer Interaction Series. Springer London, 2011 (cited on page 73).
- [3] S. Alter. A Taxonomy of Decision Support Systems. *Sloan Management Review*, 19(1):39–56, 1977 (cited on pages 7–9).
- [4] M. Andersen, A. Guillemin, M. L. Amundadottir, and S. Rockcastle. Beyond Illumination: An Interactive Simulation Framework for Non-visual and Perceptual Aspects of Daylighting Performance. In *13th Conference of International Building Performance Simulation Association*, volume 1, pages 2749–2756, 2013 (cited on page 29).
- [5] G. Andrienko and N. Andrienko. Visual Exploration of the Spatial Distribution of Temporal Behaviors. In *Proceedings of the Ninth International Conference on Information Visualisation (IV'05)*, pages 799–806, 2005 (cited on page 72).
- [6] G. Andrienko, N. Andrienko, U. Demsar, et al. Space, Time and Visual Analytics. *International Journal of Geographical Space , time and visual analytics*, 2010 (cited on page 70).
- [7] A. A. Angehrn and H.-J. Lüthi. Intelligent Decision Support Systems: A Visual Interactive Approach. *Interfaces*, 20(6):17–28, 1990 (cited on page 20).
- [8] E. M. Argyle, J. J. Gourley, Z. L. Flamig, T. Hansen, and K. Manross. Toward a User-Centered Design of a Weather Forecasting Decision-Support Tool. *Bulletin of the American Meteorological Society*, 98(2):373–382, 2017 (cited on page 20).
- [9] J. Ashmore and P. Richens. Computer Simulation in Daylight Design: A Comparison. *Architectural Science Review*, 44(1):33–44, 2001 (cited on page 32).

- [10] S. Attia, L. Beltran, A. d. Herde, and J. Hensen. "Architect Friendly": A Comparison of Ten Different Building Performance Simulation Tools. In *IBPSA Proceedings: Building Simulation Conference*, pages 204–211, 2009 (cited on page 16).
- [11] S. Attia, E. Gratia, A. De Herde, and J. L. Hensen. Simulation-based Decision Support Tool for Early Stages of Zero-energy Building Design. *Energy and Buildings*, 49:2–15, 2012 (cited on page 28).
- [12] Autodesk Inc. Autodesk Revit [Computer software]. URL: <https://www.autodesk.com/products/revit-family/overview> (cited on page 15).
- [13] S. Azhar. Building Information Modeling (BIM): Trends, Benefits, Risks, and Challenges for the AEC Industry. *Leadership and Management in Engineering*, 11(3):241–252, 2011 (cited on page 26).
- [14] R. Bhagavathula and R. Gibbons. Effect of Work Zone Lighting on Drivers' Visual Performance and Perceptions of Glare. *Journal of the Transportation Research Board*, 2617:44–51, 2017 (cited on page 55).
- [15] Blender Foundation. Blender 2.76: Free and Open Source 3D Creation Suite [Computer software], 2015. URL: <http://www.blender.org/> (cited on pages 2, 37, 38).
- [16] W. v. Bommel, G. v. d. Beld, and M. v. Ooijen. Industrial Lighting and Productivity. *Philips Lighting*, 12(10):18–21, 2002 (cited on page 29).
- [17] L. Breiman. Random Forests. *Machine Learning*, 45(1):5–32, 2001 (cited on page 90).
- [18] I. Brewer, A. MacEachren, H. Abdo, J. Gundrum, and G. Otto. Collaborative Geographic Visualization: Enabling Shared Understanding of Environmental Processes. In *Proceedings of the IEEE Symposium on Information Visualization 2000*, pages 137–141, 2000 (cited on page 71).
- [19] J. Brunner, E. Chuang, C. Goldzweig, et al. User-centered Design to Improve Clinical Decision Support in Primary Care. *International Journal of Medical Informatics*, 104:56–64, 2017 (cited on page 20).
- [20] J. D. Bullough, U. C. Besenecker, J. D. Snyder, and N. P. Skinner. Work Zone Lighting and Visual Performance. *Journal of the Transportation Research Board*, 2337:25–34, 2013 (cited on page 55).
- [21] T. Catarci, M. Costabile, S. Levialdi, and C. Batini. Visual Query Systems for Databases: A Survey. *Journal of Visual Languages and Computing*, 8:215–260, 1997 (cited on page 71).
- [22] V. M. Cavalcanti. Towards a Visual Query System for Spatio-Temporal Databases. In *Visual Languages for Interactive Computing: Definitions and Formalizations*, number March, pages 158–173. 2008 (cited on page 71).

- [23] J. Cegarra and W. v. Wezel. Revisiting Decision Support Systems for Cognitive Readiness. *Journal of Cognitive Engineering and Decision Making*, 6(3):299–324, 2012 (cited on page 15).
- [24] H. J. Chang, D. S. Song, P. J. Kim, and J. Y. Choi. Spatiotemporal Pattern Modeling for Fault Detection and Classification in Semiconductor Manufacturing. *Young*, 25(1):72–82, 2012 (cited on page 70).
- [25] D. E. Christakou and C. N. D. Amorim. Daylight Simulation: Comparison of Softwares for Architect’s Utilization. In *IBPSA Proceedings: Building Simulation Conference*, pages 183–190, 2005 (cited on page 31).
- [26] Comité Européen De Normalisation. Light and Lighting - Lighting of Workplaces — Part 1: Indoor Work Places. EN 12464-1, 2011 (cited on pages 29, 35).
- [27] C. Courage and K. Baxter. *Understanding Your Users: A Practical Guide to User Requirements Methods, Tools, and Techniques*, volume 2 of number 4 in *Morgan Kaufmann series in interactive technologies*. Morgan Kaufmann, 2005 (cited on page 20).
- [28] M. D. Crossland. *Decision Support Systems*. In *Encyclopedia of GIS*. S. Shekhar, H. Xiong, and X. Zhou, editors. Springer International Publishing, Cham, 2017, page 460 (cited on page 8).
- [29] W. Dangelmaier, M. Fischer, J. Gausemeier, et al. Virtual and Augmented Reality Support for Discrete Manufacturing System Simulation. *Computers in Industry*, 56(4):371–383, May 2005 (cited on pages 13, 14).
- [30] DesignBuilder Software Ltd. Design Builder [Computer software]. URL: <https://www.designbuilder.co.uk/> (cited on page 15).
- [31] DIAL GmbH. DIALux evo [Computer software], 2017. URL: <https://www.dial.de/en/dialux/> (cited on pages 31, 33).
- [32] S. Diehl, F. Beck, and M. Burch. Uncovering Strengths and Weaknesses of Radial Visualizations—An Empirical Approach. *IEEE Transactions on Visualization and Computer Graphics*, 16(6):935–42, 2010 (cited on page 75).
- [33] E. W. Dijkstra. *A Discipline of Programming*. Prentice Hall, Inc., Englewood Cliffs, N.J, 3rd edition, 1976 (cited on page 37).
- [34] G. M. Draper, Y. Livnat, and R. F. Riesenfeld. A Visual Query Language for Correlation Discovery and Management. In *Proceedings of the 2nd Annual Visual and Iconic Language Conference*, pages 14–23, 2008 (cited on page 72).
- [35] A. Drira, H. Pierreval, and S. Hajri-Gabouj. Facility Layout Problems: A Survey. *Annual Reviews in Control*, 31(2):255–267, 2007 (cited on page 28).

- [36] R. Edsall and D. Peuquet. A Graphical User Interface for the Integration of Time into GIS. In *Proceedings of the 1997 American Congress of Surveying and Mapping Annual Convention and Exhibition*, pages 182–189, Seattle, WA, 1997 (cited on page 71).
- [37] R. Ellis Jr, S. Amos, and A. Kumar. NCHRP Report 498: Illumination Guidelines for Nighttime Highway Work. *Transportation Research Board of the National Academies*, 2003 (cited on pages 57, 63).
- [38] H. B. Eom and S. M. Lee. A Survey of Decision Support System Applications (1971-April 1988). *Interfaces*, 20(3):65–79, 1990 (cited on page 12).
- [39] S. B. Eom, S. M. Lee, E. B. Kim, and C. Somarajan. A Survey of Decision Support System Applications (1988-1994). *Journal of the Operational Research Society*, 49(2):109–120, Feb. 1998 (cited on page 12).
- [40] S. Eom and E. Kim. A Survey of Decision Support System Applications (1995–2001). *Journal of the Operational Research Society*, 57(11):1264–1278, 2006 (cited on page 12).
- [41] D. Fernández Prieto, D. Zeckzer, and J. Hernández. UCIV 4 Planning: A User-Centered Approach for the Design of Interactive Visualizations to Support Urban and Regional Planning. *IADIS International Journal on Computer Science and Information Systems*, 8(2), 2013 (cited on pages 20, 22).
- [42] J. Fründ, J. Gausemeier, C. Matysczok, and R. Radkowski. Using Augmented Reality Technology to Support the Automobile Development. In *Lecture Notes in Computer Science*, part 30, pages 289–298. Springer Verlag LNC, Berlin, Heidelberg, 2005 (cited on page 13).
- [43] M. Fuge, M. E. Yumer, G. Orbay, and L. B. Kara. Conceptual design and modification of freeform surfaces using dual shape representations in augmented reality environments. *Computer-Aided Design*, 44(10):1020–1032, 2012 (cited on page 13).
- [44] J. Gudmundsson and M. Horton. Spatio-Temporal Analysis of Team Sports. *ACM Computing Surveys (CSUR)*, 50(2):22:1–22:34, 2017 (cited on page 70).
- [45] K. Haeb, S. Schweitzer, D. Fernandez Prieto, et al. Visualization of Building Performance Simulation Results: State-of-the-Art and Future Directions. *2014 IEEE Pacific Visualization Symposium*:311–315, 2014 (cited on pages 16, 33).
- [46] C. Hansen and C. Johnson. *The Visualization Handbook*. Elsevier, editor. Elsevier Butterworth-Heinemann, Burlington, MA, 1st ed. Edition, 2005, page 749 (cited on page 40).

- [47] J. Heilala, J. Montonen, P. Järvinen, et al. Developing simulation-based Decision Support Systems for customer-driven manufacturing operation planning. In *Proceedings of the 2010 Winter Simulation Conference*, pages 3363–3375, 2010 (cited on pages 18, 20).
- [48] R. Hitchcock and W. L. Carroll. DELight : A Daylight and Electric Lighting Simulation Engine. In *IBPSA Proceedings: Building Simulation Conference, August 11-14, Eindhoven, Netherlands*, pages 483–490, 2003 (cited on page 31).
- [49] T. Hong, S. Chou, and T. Bong. Building Simulation: An Overview of Developments and Information Sources. *Building and Environment*, 35(4):347–361, 2000 (cited on page 31).
- [50] Y. Hu, M. R. Luo, and Y. Yang. A Study on Lighting Uniformity for LED Smart Lighting System. *2015 12th China International Forum on Solid State Lighting, SSLCHINA 2015*:127–130, 2015 (cited on page 63).
- [51] Illuminating Engineering Society of North America (IESNA). American National Standard Practice for Roadway Lighting, 2000 (cited on page 63).
- [52] Illuminating Engineering Society of North America (IESNA). IES LM-63-02 (R2008) ANSI Approved Standard File Format for Electronic Transfer of Photometric Data and Related Information, 2008 (cited on page 38).
- [53] Integrated Environmental Solutions Limited. IES Virtual Environment [Computer software]. URL: <https://www.iesve.com/software> (cited on page 15).
- [54] ISO. ISO 13407:1999 Human-centered Design Processes for Interactive Systems, 1999 (cited on page 20).
- [55] A. Iversen, N. Roy, M. Hvass, et al. *Daylight Calculations in Practice: An Investigation of the Ability of Nine Daylight Simulation Programs to Calculate the Daylight Factor in Five Typical Rooms*. SBI, 1st edition, 2013, pages 1–54 (cited on page 32).
- [56] J. Jo, J. Huh, J. Park, B. Kim, and J. Seo. LiveGantt: Interactively Visualizing a Large Manufacturing Schedule. *IEEE Transactions on Visualization and Computer Graphics*, 20(12):2329–2338, 2014 (cited on page 18).
- [57] H. Juslén and A. Tenner. Mechanisms Involved in Enhancing Human Performance by Changing the Lighting in the Industrial Workplace. *International Journal of Industrial Ergonomics*, 35(9):843–855, 2005 (cited on page 29).
- [58] M. Kuhn. The caret Package, 2017. URL: <http://topepo.github.io/caret/recursive-feature-elimination.html> (visited on Sept. 27, 2017) (cited on page 90).

- [59] D. Lämkuil, L. Hanson, and Roland Örtengren. A Comparative Study of Digital Human Modelling Simulation Results and Their Outcomes in Reality: A Case Study within Manual Assembly of Automobiles. *International Journal of Industrial Ergonomics*, 39(2):428–441, 2009 (cited on page 14).
- [60] M. Lichman. {UCI} Machine Learning Repository, 2013. URL: <http://archive.ics.uci.edu/ml> (visited on Aug. 1, 2017) (cited on page 88).
- [61] S. Lind, B. Krassi, B. Johansson, et al. SIMTER : A Production Simulation Tool for Joint Assessment of Ergonomics , Level of Automation and Environmental Impacts. *Proceedings of FAIM 2008, 30 June–2 July*:1025–1031, 2008 (cited on page 14).
- [62] D. Lloyd, J. Dykes, and R. Radburn. Understanding Geovisualization Users and Their Requirements: A User-centred Approach. In *GIS Research UK 15th Annual Conference, 2007* (cited on page 20).
- [63] K. Lu, Y. Guo, F. Wei, and X. Xie. Spatio-temporal Data Model Enabled Real-time Monitoring System for the Discrete Manufacturing Workshop. *2015 IEEE International Conference on Information and Automation, ICIA 2015 - In conjunction with 2015 IEEE International Conference on Automation and Logistics*, (August):256–261, 2015 (cited on page 70).
- [64] A. MacEachren, A. C. Robinson, A. Jaiswal, et al. Senseplace2: Geotwitter Analytics Support for Situational Awareness. In *IEEE Conference on Visual Analytics Science and Technology (VAST)*, pages 181–190. International Cartographic Association, 2011 (cited on page 72).
- [65] R. A. Mangkuto. Validation of DIALux 4.12 and DIALux evo 4.1 Against the Analytical Test Cases of CIE 171:2006. *Leukos*, 12(3):139–150, 2016 (cited on page 31).
- [66] N. Menck, C. Weidig, and J. C. Aurich. Virtual Reality as a Collaboration Tool for Factory Planning Based on Scenario Technique. In *Procedia CIRP*, volume 7, 2013 (cited on page 14).
- [67] D. Mourtzis, M. Doukas, and D. Bernidaki. Simulation in Manufacturing: Review and Challenges. *Procedia CIRP*, 25:213–229, 2014 (cited on page 13).
- [68] National Framework for Energy Efficiency - Australia. Training Guide: The Basics of Efficient Lighting, 2009 (cited on page 33).
- [69] A. Negahban and J. S. Smith. Simulation for Manufacturing System Design and Operation: Literature Review and Analysis. *Journal of Manufacturing Systems*, 33(2):241–261, Apr. 2014 (cited on page 12).
- [70] C. E. Ochoa, M. B. Aries, and J. L. Hensen. State of the Art in Lighting Simulation for Building Science: A Literature Review. *Journal of Building Performance Simulation*, 5(4):209–233, 2012 (cited on page 32).

- [71] C. E. Ochoa, M. B. C. Aries, and J. L. M. Hensen. Current Perspectives on Lighting Simulation for Building Science. In *IBPSA-NVL 2010 Event. Eindhoven*, pages 1–9, 2010 (cited on page 31).
- [72] OECD and International Transport Forum. Road Safety Annual Report. Technical report, 2015, page 486 (cited on page 83).
- [73] OpenStudio. OpenStudio [Computer software]. URL: <https://www.openstudio.net/> (cited on page 15).
- [74] A. Osman, H. Baharin, M. H. Ismail, and K. Jusoff. Paper Prototyping as a Rapid Participatory Design Technique. *Computer and Information Science*, 2(3):53–57, 2009 (cited on page 23).
- [75] K. Papamichael, M. Siminovitch, J. A. Veitch, and L. Whitehead. High Color Rendering Can Enable Better Vision without Requiring More Power. *LEUKOS - Journal of Illuminating Engineering Society of North America*, 12(1-2):27–38, 2016 (cited on page 29).
- [76] A. Pellegrino. Assessment of Artificial Lighting Parameters in a Visual Comfort Perspective. *Lighting Research and Technology*, 31(3):107–115, 1999 (cited on page 28).
- [77] D. J. Peuquet. It’s About Time: A Conceptual Framework for the Representation of Temporal Dynamics in Geographic Information Systems. *Annals of the Association of American Geographers*, 84(3):441–461, 1994 (cited on page 70).
- [78] Plateforme Ouverte des Données Publiques Françaises. Traffic Accidents France - 2014. URL: <https://www.data.gouv.fr/> (visited on June 9, 2016) (cited on page 84).
- [79] E. Poppe and C. Elzakker. Towards a Method for Automated Task-Driven Generalization of Base Maps. *UDMS 2006 - 25th Urban Data Management Symposium*:3.51–3.64, 2006 (cited on page 20).
- [80] D. J. Power. Specifying An Expanded Framework for Classifying and Describing Decision Support Systems. *Communications of the Association for Information Systems Volume*, 13(February):158–166, 2004 (cited on pages 7, 9, 10).
- [81] D. J. Power and R. Sharda. Model-driven Decision Support Systems: Concepts and Research Directions. *Decision Support Systems*, 43(3):1044–1061, 2007 (cited on pages 11, 15).
- [82] L. Prazeres and J. A. Clarke. Communicating Building Simulation Outputs to Users. In *IBPSA Proceedings: Building Simulation Conference*, pages 1053–1060, 2003 (cited on page 33).
- [83] J. Preece, Y. Rogers, and H. Sharp. *Interaction Design*. Wiley, 1st edition, 2002. Part 13, pages 279–315 (cited on page 21).

- [84] B. Ravani, W. White, K. Wehage, and H. M. Tabatabaee. Solar Lighting Evaluation for Highway Applications - An Evaluation of a Solar Lighting Trailer. Technical report, AHMCT Research Center, UC Davis, Davis, 2016 (cited on pages 57, 58).
- [85] K. El-Rayes and K. Hyari. CONLIGHT: Lighting Design Model for Nighttime Highway Construction. *Journal of Construction Engineering and Management*, 131(April):467–476, 2005 (cited on page 63).
- [86] Real Time Statistics Project. Internet Live Stats. URL: <http://www.internetlivestats.com/twitter-statistics/> (visited on Feb. 29, 2016) (cited on page 82).
- [87] C. Reas and B. Fry. *Processing: A Programming Handbook for Visual Designers and Artists*, volume 54 of number 2. The MIT Press, 2007, pages 1–736 (cited on page 21).
- [88] Relux Informatik AG. ReluxDesktop [Computer software], 2017. URL: <https://relux.com/en/relux-desktop.html> (cited on pages 31, 33).
- [89] A. C. Robinson, D. J. Peuquet, S. Pezanowski, F. A. Hardisty, and B. Swedberg. Design and Evaluation of a Geovisual Analytics System for Uncovering Patterns in Spatio-Temporal Event Data. *Cartography and Geographic Information Science*, 2016 (cited on page 72).
- [90] M. W. Rohrer. Seeing is Believing: The Importance of Visualization in Manufacturing Simulation. In *Proceedings of the 32nd Conference on Winter Simulation*, WSC '00, pages 1211–1216, San Diego, CA, USA. Society for Computer Simulation International, 2000 (cited on page 19).
- [91] P. Romanski and L. Kotthoff. FSelector: Selecting Attributes, 2016. URL: <https://cran.r-project.org/package=FSelector> (visited on Oct. 16, 2017) (cited on page 90).
- [92] G. G. Roy. A Comparative Study of Lighting Simulation Packages Suitable for use in Architectural Design. Technical report, Technical Report. School of Engineering Murdoch University, Australia, 2000 (cited on pages 31, 32, 38).
- [93] M. Sadeghipour Roudsari. Ladybug+Honeybee [Computer software]. URL: <http://ladybug.tools> (cited on page 15).
- [94] S. Shikder, A. Price, and M. Mourshed. Evaluation of Four Artificial Lighting Simulation Tools with Virtual Building Reference. In *Proceedings of European Simulation and Modelling Conference*, pages 77–82, Leicester, UK, 2009 (cited on pages 31, 33).
- [95] B. Shneiderman. The Eyes Have It: A Task by Data Type Taxonomy for Information Visualizations. In *Proceedings 1996 IEEE Symposium on Visual Languages*, pages 336–343. University of Maryland, Department of Computer Science, IEEE Comput. Soc. Press, 1996 (cited on pages 71, 75).

- [96] R. Sibois, K. Salminen, M. Siuko, J. Mattila, and T. Määttä. Enhancement of the Use of Digital Mock-ups in the Verification and Validation Process for ITER Remote Handling Systems. *Fusion Engineering and Design*, 88(9-10):2190–2193, 2013 (cited on page 14).
- [97] J. S. Smith. Survey on the Use of Simulation for Manufacturing System Design and Operation. *Journal of Manufacturing Systems*, 22(2):157–171, 2003 (cited on page 12).
- [98] K. Smparounis, K. Alexopoulos, V. Xanthakis, et al. A Web-based Platform for Collaborative Product Design and Evaluation. In *2009 IEEE International Technology Management Conference (ICE)*, pages 1–9, 2009 (cited on pages 14, 15).
- [99] C. Snyder. *Paper Prototyping: The Fast and Easy Way to Design and Refine User Interfaces*. Morgan Kaufmann, 1st edition, 2003 (cited on page 21).
- [100] Solemma LLC. Diva for Rhino [Computer software]. URL: <http://diva4rhino.com/> (cited on page 15).
- [101] P. K. Soori and S. Alzubaidi. Study on Improving the Energy Efficiency of Office Building’s Lighting System Design. In *2011 IEEE GCC Conference and Exhibition (GCC)*, pages 585–588, Dubai, UAE, 2011 (cited on page 31).
- [102] J. Sorger, T. Ortner, C. Luksch, et al. LiteVis: Integrated Visualization for Simulation-Based Decision Support in Lighting Design. *IEEE Transactions on Visualization and Computer Graphics*, 22(1):290–299, 2016 (cited on pages 17, 30).
- [103] R. Southal. VI Suite [Computer software]. URL: <http://arts.brighton.ac.uk/projects/vi-suite> (cited on pages 2, 15).
- [104] R. Southall and F. Biljecki. The VI-Suite: A Set of Environmental Analysis Tools with Geospatial Data Applications. *Open Geospatial Data, Software and Standards*, 2(1):23, 2017 (cited on page 39).
- [105] R. H. Sprague. A Framework for the Development of Decision Support Systems. *MIS Quarterly*, 4(4):1–26, 1980 (cited on pages 7, 8).
- [106] S. Srivastav, S. Lannon, D. K. Alexander, and P. Jones. A Review and Comparison of Data Visualization Techniques Used in Building Design and in Building Simulation. In *IBPSA Proceedings: Building Simulation Conference*, pages 1942–1949, 2009 (cited on page 33).
- [107] Standards Australia. Interior and Workplace Lighting — Part 1: General Principles and Recommendations. AS/NZS 1680.1:2006, 2006 (cited on page 29).
- [108] State of California Department of Transportation. California Manual on Uniform Traffic Control Devices, 2014 (cited on pages 3, 55).

- [109] G. Sun. A Digital Mock-up Visualization System Capable of Processing Giga-scale CAD Models. *Computer-Aided Design*, 39(2):133–141, 2007 (cited on page 14).
- [110] W. S. Sun, C. L. Tien, J. W. Pan, et al. Simulation and Comparison of the Lighting Efficiency for Household Illumination with LEDs and Fluorescent Lamps. *Journal of the Optical Society of Korea*, 17(5):376–383, 2013 (cited on page 31).
- [111] E. R. Tufte. *The Visual Display of Quantitative Information*. Graphics Press, Cheshire, CT, USA, 2nd. ed. Edition, 2001, page 200 (cited on page 17).
- [112] T. Tullis and B. Albert. *Measuring the User Experience*. Morgan Kaufmann, 2008, page 336 (cited on page 23).
- [113] Twitter Developers. Twitter Streaming API. URL: <https://dev.twitter.com/streaming/overview> (visited on Feb. 29, 2016) (cited on page 82).
- [114] M. S. Ubbelohde and C. Humann. Comparative Evaluation of Four Daylighting Software Programs. *ACEE Summer Study on Energy Efficiency in Buildings*, 1988:16, 1998 (cited on page 33).
- [115] USC University of Souther California. Twitter and Privacy, 2013. URL: <https://pressroom.usc.edu/twitter-and-privacy-nearly-one-in-five-tweets-divulge-user-location-through-geotagging-or-metadata/> (visited on Feb. 29, 2016) (cited on page 82).
- [116] VDI (The Association of German Engineers). VDI 4499 Part 1, 2015 (cited on page 26).
- [117] G. J. Ward. The RADIANCE Lighting Simulation and Rendering System. In *21st Annual Conference on Computer Graphics and Interactive Techniques*, pages 459–472, New York, NY, USA, 1994. arXiv: arXiv:1011.1669v3 (cited on pages 2, 31, 38).
- [118] C. Ware. *Information Visualization: Perception for Design*. D. D Cerra, editor. The Morgan Kaufmann Series in Interative Technologies. Morgan Kaufmann, 2004, page 486 (cited on page 21).
- [119] I. Wassink, O. Kulyk, B. v. Dijk, G. v. d. Veer, and P. v. d. Vet. Applying a User-Centered Approach to Interactive Visualisation Design. *Trends in Interactive Visualization*, 2008 (cited on page 20).
- [120] S. Wehrend and C. Lewis. A Problem-oriented Classification of Visualization Techniques. In *Proceedings of the 1st Conference on Visualization'90*, pages 139–143. IEEE Computer Society Press, 1990 (cited on page 21).
- [121] H. P. Wiendahl, J. Reichardt, and P. Nyhuis. *Handbook Factory Planning and Design*. Springer-Verlag Berlin Heidelberg, 1st edition, 2015 (cited on pages 25–27).

- [122] M. Wörner and T. Ertl. Visual Analysis of Advanced Manufacturing Simulations. In *EuroVA 2011: International Workshop on Visual Analytics*, pages 29–32, Bergen, Norway, 2011 (cited on page 17).
- [123] T. Wuest. *Identifying Product and Process State Drivers in Manufacturing Systems Using Supervised Machine Learning*. Springer Theses. Springer International Publishing, 2015 (cited on page 89).
- [124] P. Xu, H. Mei, L. Ren, and W. Chen. ViDX: Visual Diagnostics of Assembly Line Performance in Smart Factories. *IEEE Transactions on Visualization and Computer Graphics*, 23(1):291–300, 2016 (cited on page 17).
- [125] J. Yi, Y. A. Kang, and J. Stasko. Toward a Deeper Understanding of the Role of Interaction in Information Visualization. *IEEE Transactions on Visualization and Computer Graphics*, 13(6):1224–31, 2007 (cited on page 21).
- [126] C. Zhong, T. Wang, W. Zeng, and S. Müller Arisona. Spatiotemporal Visualisation: A Survey and Outlook. In S. M. Arisona, G. Aschwanden, J. Halatsch, and P. Wonka, editors, *Digital Urban Modeling and Simulation*, pages 299–317. Springer Berlin Heidelberg, Berlin, Heidelberg, 2012 (cited on page 73).
- [127] B. Zhu and H. Chen. *Information Visualization for Decision Support*. In *Handbook on Decision Support Systems 2: Variations*. Springer Berlin Heidelberg, Berlin, Heidelberg, 2008, pages 699–722 (cited on page 19).
- [128] Zumtobel Lighting GmbH. *The Lighting Handbook*. Dornbirn, Austria, 4th edition, 2013 (cited on page 33).

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Hüb, K., Schweitzer, S., Fernández Prieto, D., Hagen, E., Engel, D., Böttinger, M., Scheler, I., (2014) Visualization of Building Performance Simulation Results: State-of-the-Art and Future Directions. IEEE PacificVis Visualization Notes Short Paper Track, 2014. Yokohama, Japan.

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Fernández Prieto, D., Zeckzer, D., Hernández, J. T. (2013). UCIV 4 Planning: a User-Centered approach for the design of interactive visualizations to support urban and regional planning. IADIS CGVVCVIP 2013, pp. 81-90, 2013. Prague, Czech Republic.

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