Integrated Networked Streetlighting Infrastructure Simulation with Crossing as Use Case

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***Abstract*—The main infrastructural parts of urban intersections are road marks, traffic lights, and lighting. Signaling – except for metal signs – is always realized as intelligent systems. In case of lighting systems, a trend for including intelligence into the luminaries for remote control and diagnosis applications can also be recognized. The increase in smartness comes at the cost of increased energy consumption. This paper describes a simulation first principle based system design of future intelligently managed street luminaries as smart lighting control system. Typical use cases were found and a simulation platform designed, to calculate estimated energy savings compared to regular LED-based light solutions, already reducing considerable lighting infrastructure costs. The paper presents a unique approach of mapping light area comparisons to simplified percentages and a promising simulation results of soon to be tested overall system energy efficiency increases by more than 20 % and CO_2 reductions without compromising traffic safety while maintaining and even increasing smart features of tomorrows critical infrastructure.**

***Index Terms*—traffic lighting, smart lighting control, public lighting simulation**

I. Introduction

Recent savings of deployment of LED-based lights into luminaries to reduce energy consumption in street lighting infrastructure is currently suffering a rebound effect from the increased energy consumption of merely adding capabilities, functionalities to the present systems. Intersections in rural and urban areas consist predominantly of three main traffic shaping-components: road marks, public lighting, and traffic lights. With the exception of metal signs, the components are always realized as energy consuming, increasingly smart systems, often providing multiple functionalities [1]. The mentioned three components could be categorized as safety-related systems, providing heavily regulated and strictly enforced safety functions, and non-safety-related systems. Traffic lights (i.e., traffic lights and traffic light controller) are safety-related signaling components, which means, there is little room for reductions to play with because a failure can compromise traffic safety [2]. Non-safety-related systems, such as electronic displays (e.g., LED-based variable message signs), and intelligent lighting systems, on the other hand, are utilized as non-safety-related components, offering remote control and diagnosis services, provide additional local intelligence, and future applications [3]. Currently though, especially outside of big cities, in smaller towns and municipalities, similar to safety-related traffic lights, each function for each component is separately realized, and each system operated on its own as an isolated application in a closed way. However, most of the cities in Europe are small to medium-sized municipalities often requiring customized solutions. For example, in Austria, just 11 % of the cities have more than 5 000 inhabitants. In [7] it was hypothesized that the energy efficiency of non-safety-related components could be increased by more than 20 %, utilizing the synergetic potential of some components.

From a technical point of view, this is only partly reasonable for the safety-related signaling system due to its high demands on safety integrity. Therefore, a commonly used infrastructure like a management-platform or pool of data does not exist. The effort for installation, setup, operation, and maintenance are necessary for every single system, which leads to higher costs, a higher overall energy consumption, and less functionality than an integrated solution could provide. Additionally, it has to be mentioned that especially in the safety-related domain, it is common to use proven technology already in use; however those solutions, almost by definition, are lagging behind state-of-the-art; hence, they cannot reach their full energy savings potential. New technological approaches can lead to significant reduction of the energy consumption of the components currently in use [5].

In Section II this paper provides a holistic concept approach for creating infrastructure components able to integrate and adopt intelligent communication modules, aid communication between different units and components of a signaling system. Section III describes the simulation environment and its energy saving potential along a traffic crossing use case focusing on public lighting. Section IV details measurements, variations, and the impact on pedestrians, and the final chapter provides a summary, a discussion of the results, and furthermore some suggestions for further extension in the section V-B.

II. Method

This paper aims to provide a simulation-first description towards a prototype of an infrastructure management platform, creating the missing pool of data, enabling openly standardized access to it, and effectively enabling a synergetic and symbiotic use of common components, functions, and infrastructure. The overall goal of the work is to integrate, all three, formerly only mechanically integrated but effectively stand alone, heterogeneous systems (traffic light, optical displays, and lighting) installed at intersections, using communication interfaces, providing a higher order management system.

A. Design Principipals and Evaluation Approach

To achieve the aforementioned integration, the safety-related system needs to be adapted to include a suitable communication network between a traffic light and controller. This novel control system replaces the currently used control and monitor mechanism, which is based on the measurement of the power loss. The non-safety-related system is designed to use a homogeneous wireless network that integrates communication modules developed prior and described in [6]–[8]. All systems can be integrated into a management system for control and maintenance. Open communication interfaces, as well as modular system architecture, were the basic design principles of the system. The physical housing of the traffic lights was enhanced so sensors can be mechanically integrated. The focus of this paper though is not the physical design and implementation of the integration, but the simulation-first principal.

To identify various benefits of the system solution, a three-step evaluation approach was specified:

1) specify use cases, evaluation parameters for energy efficiency, traffic safety and user acceptance, and collect real-life data
2) simulate the use cases and its associated scenarios
3) identify some use cases to be evaluated on the road

B. System Design Public Lighting

To facilitate the integration of formerly self-contained components or sub-systems, while ensuring traffic safety during physical trials of the system developed, the first target was public lighting. The system design for integrating public lighting was based on open standards for a secure and reliable design. An example of modular components sharing resources via a management server through a ZigBee gateway as data concentrator for updating the call order of variables can be seen Fig. 1. To extend the system towards the traffic safety-related components, it would need to introduce the layered communication approach with an additional reading only connection from the traffic light controller towards the business logic of the management server as well. All potentially synergetic or shared systems this way are merged into a management platform for control and maintenance, with particular emphasis on modularity and open interfaces. All sensor types are connected via a sensor interface and possibly aggregated through a data concentrator. Thus, by integrating and adapting intelligent communication modules and sensors, the communication between units in a public lighting system and the use of open interfaces, smart service can be created.

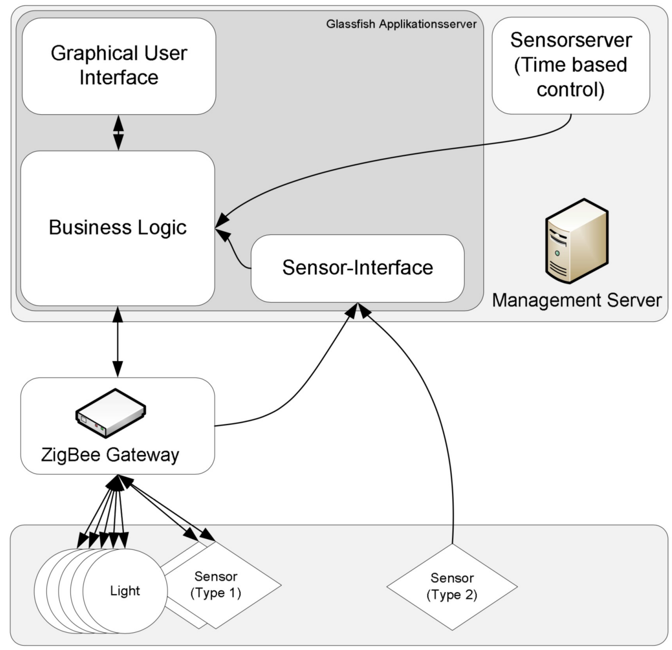

Fig. 1. Components involved in call order of `updateVariables` method example in non-safety-related system part

The functional validation of the implemented architecture takes place concerning the following objectives:

- energy efficiency – A simulation environment is developed, providing promising simulation results towards increasing the energy efficiency of infrastructure at intersections by more than 40 % of its original value, without compromising traffic safety.
- traffic safety – Focusing on public lighting, an evaluation of violations against current product standards (e.g., ÖNORM 1053, EN 13201) is necessary during an impact analysis of the final prototype before production.
- user acceptance – The validation, which takes place in a prototypical test installation, provides valuable data for spreading the holistic idea and raising awareness among relevant stakeholders.

III. Crossroad Use Case

This section presents an overview of the considered use case, explains the underlying assumptions, and input data preparation performed. The considered use case is a typical crossroad, which consists of a central area and connecting roads (lighting areas). Different lighting areas have their management logic, which suites related requirement and traffic conditions. Fig. 2 depicts a crossroad with four connected roads. For the use case, only the West and East roads in lighting area 1 and 2 are equipped with smart lighting control, and the North and South parts have a traditionally fixed level of light during the operation time.

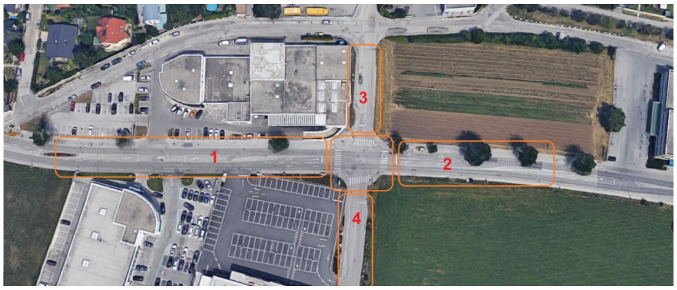

Fig. 2. Depiction of five lighting areas in selected crossroad use case, with area one being west

This paper is building on results published in [2], [9] which mainly focus on straightforward roads and streets. In these roads, mainly the total number of cars in the lighting area 1 and lighting area 2 determines the light level.

In this presented use case, the crossroad lighting area, the number of cars at the crossroad, and absence/presence of pedestrians to determine the light levels. Parallel to the physical design and implementation of the smart lighting control, an accurately simulated project was developed by using the AnyLogic development environment. In the simulation, the length of the area, average speed, and the number of cars are initial settings which are used to indicate light levels of the areas. Because of different directions and lengths (Fig. 2), using average speed and the length of the crossroad for finding the passing time is not accurate enough. Instead, a simulated passing time is used, which is better fitting than just using a fixed passing time. By reducing the average pedestrian passing time, consumed energy slightly reduces, but it has a side-effect of increasing the number of light level changes during the operation time.

A. Simulation Model Description

As already mentioned, the simulation does not consider optical displays. For traffic simulation structure, for every passing car, the destination is determined by the lane of the road. In this approach, three lanes are considered for all roads. In the driving direction, the left lane is for turning left, the middle one is for straightforward driving, and the right lane is for turning right. This way, the destinations of simulated cars are pre-defined by lanes they enter. With this approach, multiple kinds of traffic data can be fed into the simulator, to observe the system behavior.

Input data methods for two steps were implemented. First, simulated traffic data provided by a project partner, based on real crossroad observation and video processing was used. This data leads to a definition of rates of cars for every lane. As results, Table I shows the calculated percentages as rates of cars for every lane. In a second step, the pre-calculated rate of cars for every lane of the roads was used as input data. In this way, the simulator generates traffic data based on the initially measured data.

TABLE I
LANES SHARE FROM TRAFFIC AT A THREE ROAD LANE CROSSING (R1-12) CALCULATED FROM OBSERVATION AND VIDEO PROCESSING

		R12	R11	R10		
		0.017	0.004	0.046		
R1	0.017				0.033	R9
R2	0.386				0.348	R8
R3	0.014				0.017	R7
		0.068	0.017	0.032		
		R4	R5	R6		

B. Motivation for Simulation first

In a street lighting system, parameters such as system settings, traffic, weather conditions, and controlling strategy of the lighting system can affect the performance of a lighting system. In the real-world, it is tough to implement experiments to analyze the influence of different scenarios in street lighting systems. Because, in the first step, building a new lighting system in the real-world is expensive and time-consuming. Secondly, during the study, many experiments need to be performed while the impact of traffic behavior should be considered. In the real-world, traffic behavior is not constant and results obtained from multiple experiments based on real traffic behavior are not the same necessarily. Finally, the lighting system configurations need to be frequently changed to investigate the influence, on the whole system. In the real-world, this is difficult and costly and can have an impact on safety during regular construction work.

In some cases, a physical implementation is not accessible or even still does not exist, and investigation before installation is required while there is no chance to examine not existing systems. So instead of experimenting in the real-world, investigating the behavior of the lighting system using a simulation environment, parametrized with real-world data, is reasonable and practical. In this paper, a discrete event simulation approach by using AnyLogic development environment (AnyLogic 8 University 8.2.3) is selected. Models are developed using Road Traffic Library provided by AnyLogic. Fig. 3 depicts a visual view of the model.

Another beneficial result of the simulation is the enabled informed selection of a physical place for the implementation of the infrastructure. Real traffic sampling or simulating the traffic patterns in different candidate crossing sections creates a unique opportunity to acceptably, accurately estimate the potential energy saving for each crossroad. This data can be used to select best candidate(s) for realization.

C. Intersection Considerations

The number of cars in the intersection with the contribution of absence/presence of pedestrians in the lighting area defines the intersection light levels. Furthermore, as additional consideration, the light level of the intersection is increased to the maximum light level of connecting streets. This constraint even reduces unnecessary light level changes.

In the presented simulation model, conservatively, only the absence/presence of pedestrians at the crossroad is considered.

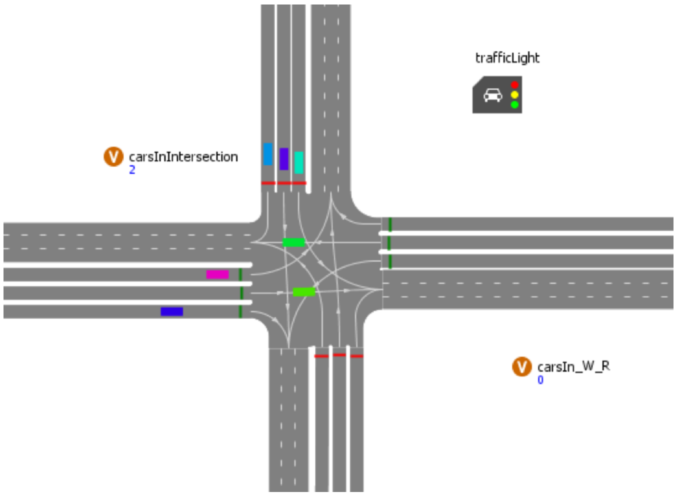

Fig. 3. Screenshot example of a running AnyLogic simulation of the intersection use case with 2 cars depicted in the middle of the intersection

After detecting a pedestrian in the lighting area, for predefined seconds, the system assumes that there is somebody in the area. If a person is waiting for the pedestrian green light, most probably, one can be detected multiple consecutive times. For the simulation, it means that there is no need to consider extra time for potential waiting for the green light. On the other hand, when a pedestrian passes from one street onto the other side of the street, they will be detected again. Consequently, the pedestrians presence time in the system is doubled at least.

IV. Simulation Results with New Energy Management Model

Previous work [6] did show that a broader assessment of energy consumption with distinct use cases needs to be investigated to benefit user safety and acceptance. This section describes different aspects of how the simulation model can allow a more comprehensive analysis.

A. Energy Efficiency Measurements

Comparing total energy consumption in one particular lighting area before and after applying a smart lighting system is meaningful, it provides the exact amount of saving energy. However, when it comes to comparison of multiple lighting areas, then the total number of luminaries in the area, similarity or heterogeneity of luminaries and minimum required light in the surface of the roads are different. To avoid the complexity of this comparison and make it easily visible in simple graphs, a unique approach for all the lighting areas is considered, and light levels of public lighting are mapped to percentages. 100 % light level means the system is operating at the predefined level of light when there is no smart lighting control in the lighting area. By applying smart lighting control, depending on the detected situation and predefined rules, the emitting light is reduced, this reduction is calculated as percentages. For example, if there is no pedestrian in the lighting area, and there is no car in the area, then the emitting light is reduced to 40 % of its original value.

On the other hand, the light level is directly related to the energy consumption in the lighting area. In other words, only one luminary acts as an indicator of the lighting area. During the simulation, consumed energy is calculated based on summarized operation time in different light levels.

B. Car rates Variations

Traffic pattern in one particular point is a dynamic parameter. It is continually changing, not only in different time of day but also for more prolonged periods, such as week and month. Start and end time of office hours in one day, work-free days during weekends or seasonal holidays are classic examples of changing traffic patterns. Besides, other reasons, e.g., road constrictions or local events, also affect the traffic patterns. Instead of trying to match this type of complexity, a simple approach as a number of cars per hour is chosen, which can be adapted to all of the before-mentioned traffic patterns.

In this experiment, numbers of cars per hour are increased from 0 to 2 000. Pedestrians and pedestrian active time are fixed in the intersection. It can be predicted that by increasing the traffic volume, the system operates at the higher light levels and consequently, the potential of energy saving reduces.

Obtained results of the simulation, depicted in Fig. 4, shows that by increasing the number of cars per hour, energy consumption increases and, depending on the initial settings, the system reaches a saturation point, as hypothesized. For example, in the intersection lighting area, when the number of cars per hour reaches to 1 300, then the saving potential is around 2 %. This simulation result translates into most significant savings for rural areas without much traffic.

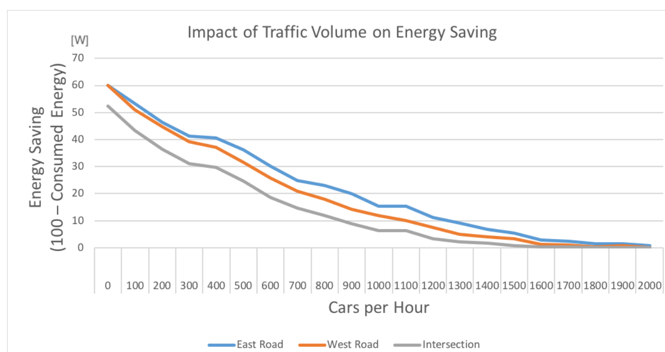

Fig. 4. Simulated energy savings impact results for increasing cars per hour

Changing the initial setting can affect the presented graph in Fig. 4, but the general shape of graphs can still uphold the same trend. It is evident, that increasing the traffic decrease the chance of energy saving. Consequently, in the developed simulated model, it has been assumed that changing non-safety parameters such as adopting smart lighting and reducing the light levels in the absence of pedestrians or presence of fewer cars in the lighting area (not violating existing standards), had no effect on the safety of pedestrians and occupants in the cars. Clearly, accepted and considered lighting standards in the

lighting systems have defined the minimum light level required in streets in all possible conditions, including different traffic patterns, absence, and presence of pedestrians.
The validation, which takes place in a prototypical test installation, provides valuable data for achieving the desired objective. These objectives are defined as energy efficiency, traffic safety, and user acceptance [7].

C. Impact for Pedestrians

For investigating the impact of pedestrians on the energy consumption (or energy saving), in the simulated intersection was calculated as well. In a first step, it has been assumed that there are no cars in this scenario and the only activator of the lighting system are pedestrians.
In a parameter variation simulation, the number of pedestrians is increased from 0 to 300 pedestrians per hour. This simulation is repeated for 3 different values of pedestrian active time. This parameter indicates the duration of considering the pedestrian in the lighting area from last pedestrian detections. In this particular scenario, there is no car in the area, so the light level always remains in the lower levels. The simulation only switches between no car, no pedestrian light level (40 %) and no car, with pedestrian light level (50 %). Consequently, the saving energy potential percentages comparing to the system which is running at 100 % light level are $100-40=60$ and $100-50=50$. Hence, the simulation is independent of values depicted as a vertical legend in Fig. 5. These numbers define the energy saving potential in the absence or presence of pedestrians.

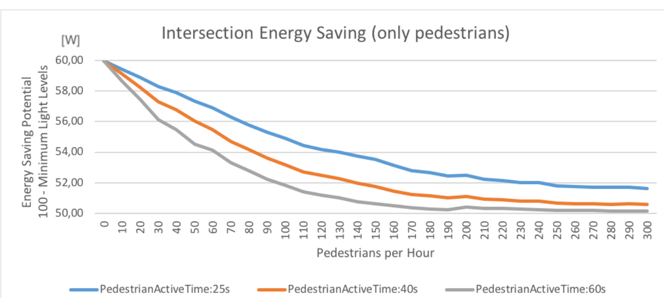

Fig. 5. Simulated energy savings impact results for increasing pedestrians per hour

In real-world low traffic places, car traffic and pedestrian traffic rates vary during the day. The identified simulated functions for cars and pedestrians per hour can help even smart offline systems to calculate energy savings of public lighting and at break-even points choose the light level in smart settings.

V. Conclusion

This paper describes a holistic concept for managing the infrastructure at an intersection by integration and adaption of intelligent communication modules, communication between different units and components of a signaling system, and open communication interfaces. Selected results of a simulation first principle with provided traffic data were presented. A unique approach of mapping light area comparisons to simplified percentages was shown and a promising potential energy saving as high as 40 % simulated. Another potential usage and motivator for developing the simulation was to use it as a practical tool, to determine the best use cases and ordering the candidate crossroads for selecting first ones to be equipped with smart lighting control and implemented in the real-world. Prototypes were realized and are going to be installed at a test installation after integrating learnings of presented simulation results.

A. Discussion

By considering the pedestrian active time 40 s series in Fig. 5, it can be observed that if there is no pedestrian in the area, saving energy is 60 % and by increasing the number of pedestrians, saving energy drops to almost 50 %. The point corresponding to the 70 pedestrians per hour shows that the saving potential is almost in the middle of vertical legend. In other words, in this simulation, if there are 70 pedestrians per hour, there is a chance for reducing the energy consumption to half of the difference of minimum light level with pedestrians and minimum light level without pedestrians.
The primary source of energy saving in this project comes from this fact that based on accepted public lighting standards, the minimum required light level is defined based on a statistical observation of cars and pedestrians in the lighting area. When there is no possibility of detecting the cars and pedestrians, the lighting system has to cover the extreme cases. It means that, if there are no facilities for pedestrian detection, then the lighting system has to consider that pedestrians are present there in all operation time. By introducing any smart lighting system, it is possible to reduce the necessary light level and consequently reduce the energy consumption. This reduction is directly related to the minimum light level. As it is depicted in Fig. 5, maximum energy saving is 60 % because the minimum possible light level in the absence of cars and pedestrians is 40 % in the scenario. The luminous intensity of 40 % corresponds with a lighting class in the European standard EN 13201. By increasing the number of cars and pedestrians, the system operates in the higher light levels and reduces the chance of energy saving, until it reaches a saturation point. For example Fig. 5 shows that if there are more than 200 pedestrians per hour in the intersection, almost there is no chance for energy saving.
In the same way, Fig. 4 shows that by increasing the number of cars in the lighting area the chance of energy saving reduces. So in both graphs, by increasing active entities, the chance of energy saving reduces and naturally Fig. 4 and Fig. 5, are similar.

B. Outlook

Today, the increase of functionality has been done on a feature basis and not approached in a holistic way. Future work can identify additional energy efficiency measures of non-safety-related lighting solutions, by utilizing the synergetic potential of different functions and services realized and shifting the viewpoint from components towards functions.

Even though, the life cycles in traffic infrastructure are 20-25 years, digitalized and smart solutions have been introduced step by step. It is crucial to present each customer its benefits linked to the provided Solution to increase the penetration rate of intelligent infrastructure. Therefore, the evaluation of a test installation regarding energy efficiency, traffic safety, and user acceptance helps to gain valuable data and conclusions for later dissemination activities to spread the idea of a holistic approach and to raise the awareness of relevant stakeholders. Test installations also support the international co-creating participation of different stakeholders.

In the current results, based on average traffic patterns and best practices, the optimum configuration for the lighting system is selected. Future word would be adding additional algorithms which, based on local parameters such as weather conditions and traffic patterns, react and switch between predefined lighting logics. We hypothesize this action can not only increase the efficiency of the system but also remove the initial configuration process. In the authors' opinion, the basic functionality of the street lighting system is well developed, and only the future can tell if now is the right time for broadly adding artificial intelligence and machine learning to these systems and applications.

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