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WORKFORCE WELLBEING MANAGEMENT LEVERAGING SEMANTIC KNOWLEDGE GRAPH

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Abstract: Workforce wellbeing is of strategic importance in new economy, not only for enterprises but for SMEs as well. Fatigue is one of key factors which affect workforce wellbeing, particularly in risk-sensitive environments such as manufacturing. Despite that importance of fatigue is identified in literature, this aspect is not much leveraged in existing solutions aiming high levels of effectiveness by optimal operation planning and scheduling. In this paper, a solution aiming optimal fatigue-aware planning and scheduling in manufacturing based on semantic knowledge graphs is presented. Thanks to adoption of ontologies, our approach enables seamless integration of heterogeneous data sources including legacy ERP systems, external services as well as sensors such as IoT wearable devices. Complementing the planning and scheduling solution, two additional apps are developed: 1) mobile app for physiological data acquisition using wearable device for purpose of fatigue estimation 2) shopfloor monitoring web app with machine operation instructions incorporated.

Keywords: workforce wellbeing, welfare, ontology, semantics, fatigue, planning and scheduling, knowledge graph.

1. INTRODUCTION

Healthy and productive workforce is a vital asset for any organization, as it drives success and fosters positive reputation. Hence, employers aim to create a workplace environment that promotes workforce wellbeing, leading to increased job satisfaction, lower turnover rates, and improved productivity (Bennett et al., 2017). Workforce wellbeing covers mental, emotional, and physical health of employees on a workplace. Additionally, it also involves the adoption of supportive environment which allows individuals to thrive both personally and professionally. Therefore, employers are increasingly recognizing the strategic importance of workforce wellbeing, not only as a moral imperative but also as a key factor in business success.

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Well-rounded approach to workforce wellbeing includes several components (Bennett et al., 2017; Tshering, 2022): 1) *mental health support* - involves providing resources for managing stress, anxiety, and other mental health challenges; 2) *work-life balance* - promoting a healthy balance between work and personal life, which can be achieved through flexible work arrangements, remote work options and other policies that encourage taking time off when needed; 3) *physical health and fitness* - encouraging physical activity and healthy habits can have a significant impact on employee wellbeing, so the employers can offer fitness programs, gym memberships, or on-site exercise facilities, as well as promote healthy eating options in the workplace; 4) *positive workplace culture* – adopting inclusivity, respect, and open communication, so the employees can feel valued and heard; 5) *professional development and growth* - offering opportunities for learning and career advancement can boost employee morale and wellbeing, which employers can support by providing training programs, mentorship, and clear pathways for career progression; 6) *social connections and team building* - building strong social connections among employees can enhance workplace morale and overall wellbeing, which can be facilitate through activities such as team-building and other social events 7) *recognition and rewards* - recognizing employee achievements and providing rewards for outstanding performance can boost morale and encourage a positive work environment.

On the other side, fatigue represents critical factor affecting workforce wellbeing and productivity (Gempur, 2024). It is often described as feeling of weariness, tiredness or lack of energy (NIOSH, 2024). Therefore, it can impact an individual's ability to perform tasks efficiently, make decisions, and maintain a positive outlook. Despite that fatigue management importance and effects in manufacturing are identified (Islam at al., 2015; Shuling, & Hall, 2021), not many works in the existing literature actually incorporate it for purpose of more efficient planning (Tao et al., 2024).

Therefore, in this paper, we propose a solution leveraging ontologies and semantic knowledge graph which enables seamless integration of heterogeneous data sources (ERPs, IoT devices) for purpose of fatigue-aware manufacturing planning and scheduling. The main goal of such approach is to make use of fatigue information together with other aspects related to manufacturing resource availability - not only to reduce the probability of risks for injuries and damages within the manufacturing area, but also increase the wellbeing of manufacturing workforce, which could bring additional benefits – such as increased productivity and higher worker satisfaction. Additionally, we adopt similar approach of semantic-based data integration for purpose of manufacturing monitoring with two goals in mind – from both manufacturing manager and worker perspectives. For manufacturing managers, it would give better overview of the current worker and equipment state, so they can act accordingly – re-schedule tasks to the workers and generate updated work plans. On the other side, for the workers, we aim to provide educational value and reduce cognitive load, leveraging the integration with machine operation instructions.

2. BACKGROUND AND RELATED WORKS

2.1. Semantic knowledge graphs

Semantic knowledge graphs represent a dynamic approach to organizing and understanding information, which does not capture only the key entities (such as people, places, or concepts), but also the relationships between them, providing a rich and interconnected view of data relevant to the domain of interest. Entities are represented as graph nodes, while edges are used to denote the relationships between them. Unlike traditional databases, semantic graphs use a flexible schema, which gives possibility for more adaptable and context-sensitive representation of knowledge. This kind of flexibility is achieved through ontologies, which define the types of relationships and entities, allowing for semantic reasoning and inference against such data representations.

There are several benefits of using such representation (Sharma, 2021): 1) *contextual understanding* – as relationships are explicitly defined, semantic knowledge graphs can capture context in a way that flat data structures cannot. This context is crucial for applications that require deeper insights into complex data and its further usage; 2) *interoperability and integration* - semantic knowledge graphs can integrate data from diverse sources, making them ideal for large-scale data aggregation and analysis, facilitating interoperability by using standards like RDF (Resource Description Framework) and OWL (Web Ontology Language); 3) *enhanced search and querying* - queries in a semantic knowledge graph can traverse relationships and extract complex patterns, leading to more nuanced and meaningful results 4) *inference and reasoning* - semantic knowledge graphs support inferencing, allowing new knowledge to be derived from existing data through logical rules, which is valuable for applications like expert systems and knowledge-based AI.

In our past works, we have successfully adopted ontologies and semantic technology in several scenarios for purpose of IoT data integration. In (Nejkovic et al., 2020), coordination based on IoT sensing devices in robotics experimental environment leveraging LiDAR and temperature values was achieved. On the other side, we used similar approach for IoT-based indoor localization system data integration in (Tosic et al., 2023).

The approach in this paper relies on proprietary Tasor ontologies for representation of various aspects related to manufacturing, such as machines, workers, their skills, materials, resources, work orders and the activities (Tosic et al., 2023). This kind of representation enables within unified semantic knowledge graph represented with respect to ontologies enables establishing interoperability, covering legacy Enterprise Resource Planning (ERPs), external services (such as machine learning or prediction capabilities) and heterogeneous IoT devices (wearables and positioning devices, for example). Furthermore, our planning framework makes use of semantic knowledge representation incorporating information from various sources in order to achieve fatigue-aware work activity scheduling.

2.2. Literature review

In the existing scientific literature, there are few works in different domains taking into account fatigue for workforce scheduling. Table 1 gives overview of these solutions, together with the underlying approaches.

On the other side, the fatigue estimation method leveraged in this paper is takes into account heart rate and acceleration sensor data coming from wearable devices worn by workers. Compared to other approaches, it provides additional flexibility, as it leverages semantic knowledge graph for data integration, which enables to conveniently add new parameters (semantic integration of various measures coming from IoT devices or ERP system). This way, our approach provides additional extendibility and flexibility compared to the existing ones. Additionally, we present practical experience from using different applications developed on top of the proposed platform deployed on IoT-on premise-Cloud continuum.

Table 1. Overview of works leveraging fatigue for workforce scheduling

Reference	Description	Method	Domain
(Thorpe et al., 2017)	Selection of team players considering their fatigue level	Analysis of heart rate variability	sport
(Ranakul et al., 2024)	Scheduling of tanker employees	Bayesian networks considering various factors: ship design, age, illness, amount of sleep	shipping
(Amindoust et al., 2021)	Fatigue-aware approach, aiming personnel planning during the COVID-19 pandemic	Genetic algorithm which takes employment and surplus costs into account	healthcare
(Bowdem et. al., 2018)	Selection of truck drivers with aim to reduce the risk of accident occurrence	Alertness level-based estimation for Vehicle Routing Problem (VRP)	transportation
(Aribi et al., 2023)	Dynamic flexible job shop-scheduling problem under workers' fatigue constraints, considering three types of unexpected events: job insertion, machine breakdown and job cancellation	Multi-objective optimization in synergy with genetic algorithm	manufacturing

3. IMPLEMENTATION OVERVIEW

When it comes to implementation, we rely on the existing proprietary Tasor SCAS platform, especially for semantic knowledge graph management on backend. The proposed approach is referred to as Fatigue aware semantics for planning and scheduling in discrete manufacturing (FASPAS). Illustration showing the overview of the underlying components behind FASPAS implementation is given in Fig. 1.

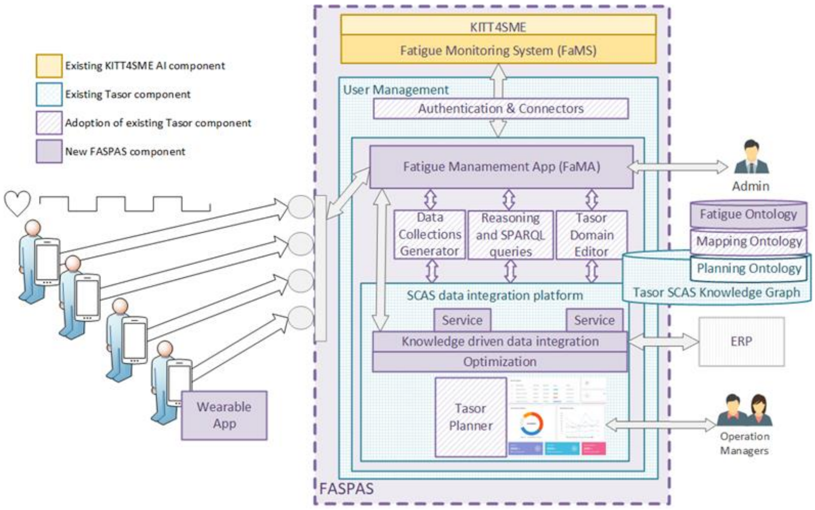

Figure 1. FASPAS implementation based on Tasor ecosystem leveraging semantic knowledge graph and ontologies

Furthermore, we develop wearable mobile applications whose goal is to acquire physiological data about employees (heart rate, acceleration). The data is collected by FAMA service that aims to further feed the Fatigue Monitoring System (FaMS) with the expected inputs. FaMS is one of KITT4SME's (KITT4SME, 2024) existing AI components which provides fatigue prediction taking into account physiological (such as heart rate) data (Rožanec et al., 2023).

Additionally, FIWARE Orion Context Broker, as part of the KITT4SME infrastructure (KITT4SME, 2024), is used for both interaction with FaMS and sensor data acquisition. For that purpose, we develop Broker Connectors Service, which provides high-level interface to data management of broker data, such as subscribing to value changes, pushing measurements, retrieval of specific values and persisting data streamed to broker. Functionalities for acquiring data from FIWARE Orion Context Broker were already introduced in (Tosic et al., 2023), but here they are extended with data persistence capabilities and customized for connecting to KITT4SME infrastructure.

On the other side, our ecosystem includes Tasor Domain Editor, which is an application for management of production resources and flows used. All reasoning in the system is based on existing efficient SPARQL query development and management tools.

The crucial ontology behind the scheduling framework is Planning Ontology, which already existed, but Mapping Ontology was extended and customized for the specific domain, while Fatigue Ontology was developed from scratch. Fig. 2 shows the segment of Planning Ontology, specifically, the part describing the concept of order.

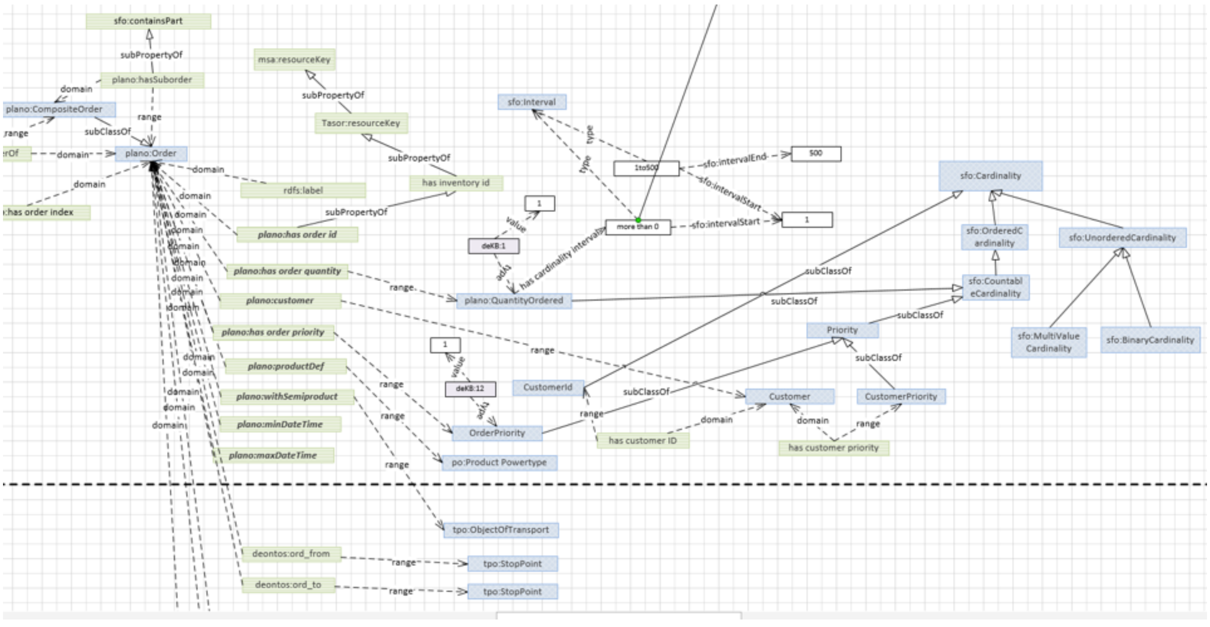

Figure 2. Segment of the Planning Ontology illustrating concept of Order

Knowledge driven data integration and optimization services were developed to connect to the existing ERP system. Finally, one of the existing Tasor Planner variants was adopted and modified accordingly to answer to requirements of the particular application, in order to generate fatigue-aware work plans based on employees' physiological data acquired by wearable devices.

Moreover, Fig. 3 shows the depiction of Fatigue Ontology. The key indicator of industrial employee fatigue monitoring domain is a Fatigue Factor, which represent an aspect which has impact on person's level of fatigue. The factors can be divided into two sub-groups – static and dynamic factors. Static factors are independent on the current circumstances and represent long-term characteristics of an employee, which cannot be changed under the environmental factors within the usual monitoring time frame. Here, we have physical characteristics, such as height, weight and gender. Moreover, the aspects of age and working experience are also taken into account, together with maximum heart rate for that person. On the other side the dynamic factors are likely to change under various environment conditions and include worker's body temperature, movement, acceleration, galvanic skin response and current heart rate. These dynamic characteristics represent either current state of the employee's physiology or describe the activity performed itself (for instance, moving or standing) and depend on external factors, such as activity type, task difficulty, part of the day and similar. The values describing dynamic aspects are collected using various environmental sensors (like cameras, proximity sensors and air parameter sensing) or wearable devices (Polar Verity Sense in our case). On the other side, current relative position of workers given in form of *(X, Y, Z)* coordinate triplet can be taken into account, especially when it comes to the aspects of shopfloor monitoring. Additionally, the role of worker and their position within the working environment like office number/room or part of the factory together with its geographical location can be of interest as well. This factory can capture additional factors which can be used for refinement when it comes to fatigue determination, such as climate (depending on geolocation of factory) and pollution (with respect to part of the factory and types of activity performed). Finally, the level of fatigue is determined by classification-based machine learning (such as Random Forest or Deep Learning neural network) algorithms and normalized to 10-step Borg scale, ranging from 0 (no fatigue) to 10 (max).

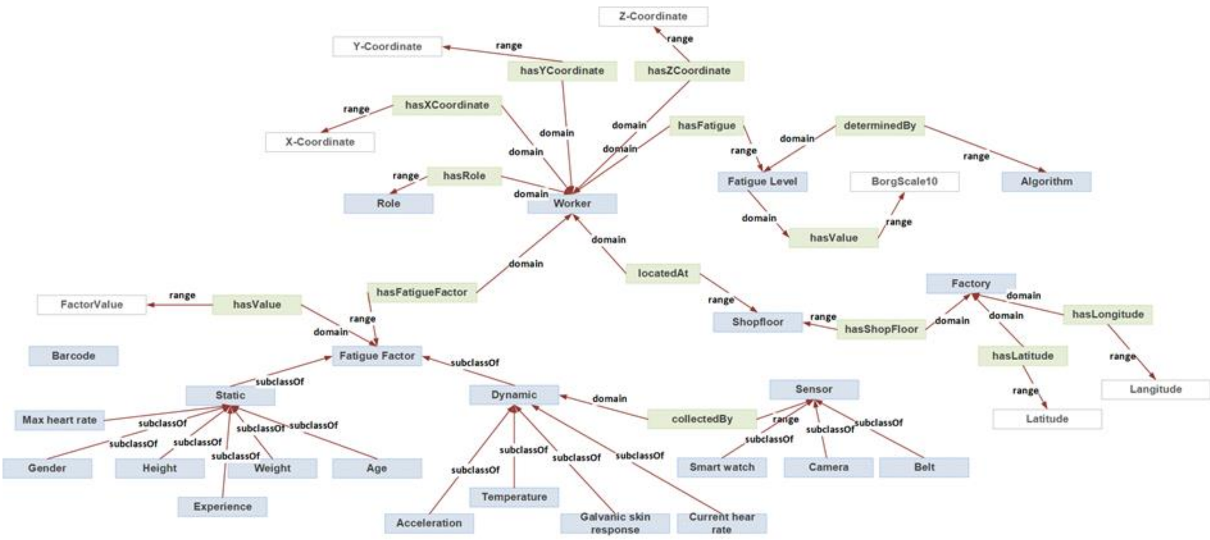

Figure 3. Fatigue Ontology

4. CASE STUDIES

4.1. Shopfloor monitoring

The goal of this case study is to provide the means for convenient shopfloor monitoring by integrating the information about workers, machines, products and other manufacturing resources thanks to semantic knowledge graph and ontologies. This way, manufacturing managers will have complete insight into the current state of manufacturing process, so additional actions can be taken in order to make work process more efficient or overcome the unexpected events. On the other side, workers will be able to quickly get the basic information about the usage of shopfloor equipment.

For this purpose, we offer a web application which is optimized for running on mobile devices and tablets as well. Apart from ERP data, this application leverages semantic integration with indoor localization data coming from WiPos-based IoT system, as described in (Tosic et al., 2023).

It offers two main views: semantic annotation and live exploration (as shown in Fig. 4). The purpose of semantic annotation view is to give ability to the manufacturing managers to map specific locations within the shopfloor to corresponding machines available within the ERP inventory data. Apart from their basic information (machine type, name, manufacturer, set of manufacturing steps which can be completed), operational instructions can be included as well, so workers can later easily find the manual, once they come close to the machine within operation monitoring view. This way, educational value is added to our solution, aiming to reduce the risk of workers using machine with lack of expertise.

On the other side, operation monitoring provides location-based exploration of shopfloor. As user walks within the manufacturing area, their location is updated and corresponding points of interest (machines) revealed accordingly, once they come near them.

Figure 4. Shopfloor monitoring case study: a) semantic annotation b) live shopfloor exploration

Demo video showing the previously described application live in action is publicly available on YouTube†.

4.2. Fatigue-aware planning in manufacturing

This case study has two parts. The first one is targeting workers in manufacturing. It is a self-monitoring Android mobile app which integrates sensor data (heart rate, acceleration, gyroscope and magnetometer) coming from wearable devices in order to estimate the current worker state, expressed as fatigue level. For this purpose, we make use of wearable device, which sends data to mobile app that forwards the measured values to FAMA service. Finally, FAMA service streams the measured data to FIWARE Orion Context Broker, so it can be consumed by external FaMS service and value of fatigue estimated based on these measurements. In Fig. 5, the two main screens of mobile app used by workers are shown: a)

† https://www.youtube.com/watch?v=ajMcmGThpYw

current physiological state – includes values of fatigue, heart rate and acceleration b) history – visual representation of critical measurements over time, while period can be specified by user.

On the other side, the second part of this case study is web app aimed to be used by manufacturing managers. It offers the following screens: a) fatigue monitoring – complete insight into current fatigue estimation for all the active workers based on wearable device data integration b) planning – generation of fatigue-aware manufacturing plan, taking into account both the measured data and ERP (worker skills, available machines, products and underlying processes). The objective of scheduling process is to allocate physically less demanding tasks to workers with higher current fatigue value and vice-versa. Apart from increased manufacturing efficiency and injury risk minimization, we aim to achieve improved workforce wellbeing and worker satisfaction as well. Illustration of case study usage from manager's point of view is given in Fig. 6. Finally, the live action showcase for this case study can be found as footage[‡].

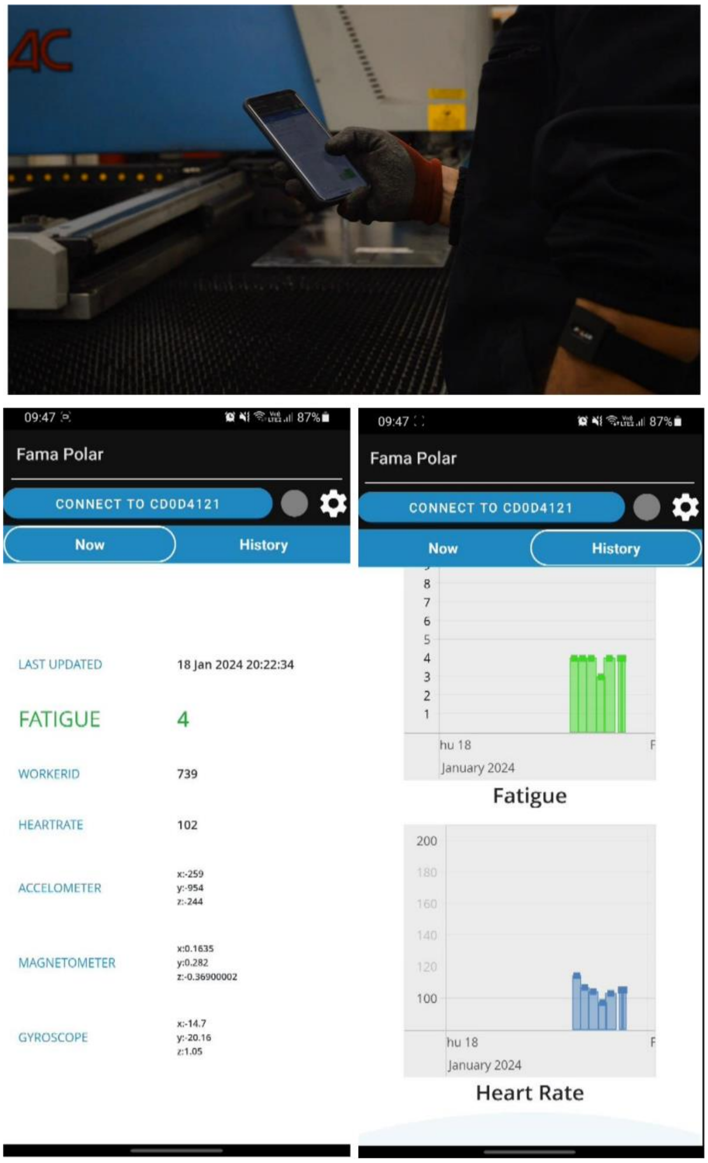

Figure 5. Worker fatigue self-monitoring mobile app: a) current status b) history

[‡] https://www.youtube.com/watch?v=meBgrpsnfZg

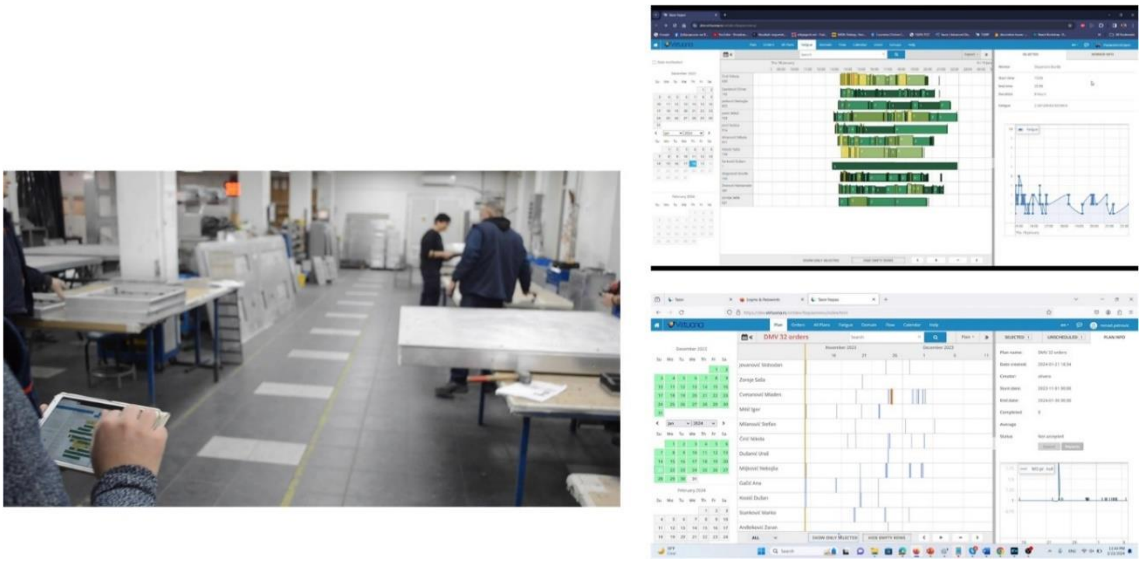

Figure 6. Manufacturing manager web app: a) fatigue overview b) planning

5. CONCLUSION

In this paper, we introduced a semantic knowledge graph-driven approach to integration of enterprise data resources – legacy ERPs and IoT devices on the other side (wearables and localization system). Moreover, such representation is further leveraged for operation planning in manufacturing scenario in order to increase the workforce wellbeing by incorporating the information about worker's fatigue among other factors. Additionally, we provide supportive mobile and web apps which would make the whole process more convenient to both the manufacturing managers and workers. According to our experience, one of the main advantages of such approach is extendibility. Representation of manufacturing knowledge in form of semantic graph gives ability to later dynamically integrate additional factors and data sources (either devices or external services). In future, we plan to explore the utilization of Large Language Models (LLMs) on top of our semantics-driven approach in order to automatize as much as possible the following steps applied on ontologies and semantic data: 1) creation of new domain ontologies starting from free-form text or tables; 2) construction of SPARQL queries starting from text 3) automatic code generation based on semantic representations.

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