Evaluation of shift work scheduling and overtime allocation practices using the HSE Fatigue Index: application in complex manual assembly

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Abstract. Despite the increasing level of automation and digitalization in manufacturing, manual assembly is still important. Factors affecting human performance can increase errors and generate quality issues. In this paper, we investigate how overtime allocation practices can impact the level of fatigue. The manufacturing process object of analysis face variations in production levels and staffing needs change accordingly. A total of 12 shift arrangements (six mornings and six evenings) were evaluated using the Fatigue Index developed by the Health and Safety Executive (HSE) in the United Kingdom. Results show that evening shifts are in general more sensitive to overtime allocation compared to morning shifts due to the difference in lengths and time of the day. The analysis helps supervisors to take into account the different impacts of overtime allocation practices on potential levels of fatigue depending on the type of shift and the shift arrangement.

Keywords: manual assembly, human performance, fatigue index, shift arrangement, overtime allocation

1. Introduction

In recent times, advances in automation and digitalization of various processes in manufacturing have been at the center of the fourth industrial revolution, better known as Industry 4.0 (Kagermann et al. 2013; Hempel & Glemser 2017). However, despite this trend on automation and digitalization, several manufacturing domains still depend on manual work and many products are still being assembled by hand (Botti et al. 2017; Correia et al. 2018; Judt et al. 2020). But manual work and particularly manual assembly tasks are sensitive to human error which in turn represents a potential source of quality issues (Falck et al. 2014; Richards 2018). For this reason, it is important to study the factors that affect human performance in order to avoid human errors and their undesirable consequences in terms of quality, productivity and safety. Fatigue is one of the factors that has been studied for decades in safety-critical domains like aviation and the nuclear and process industry because of its negative effects on human performance as well as the potentially catastrophic accidents that can result. In the case of manufacturing, Kolus et al. (2014). developed a conceptual framework exploring the relationships between poor ergonomic job design, the development of fatigue in operators, and resulting production errors. The authors identified fatigue as a frequent intermediate factor associated with increased quality deficiencies. Despite these results, it seems that, historically, the focus of attention in manufacturing has been placed on physical job demands related to biomechanical loads (Bruder et al. 2009) because of the relevance of musculoskeletal disorders (Bao 2015; Yang et al. 2020).

General fatigue and particularly, chronobiologic aspect of fatigue (time awake, circadian rhythm, and lack of sleep) has been less explored in comparison with, for example, muscular fatigue. The latter being the object of development of several rest allowance models associated to dynamic/static muscular work (Rohmert 1973; El Ahrache & Imbeau 2009). Nevertheless, shift work and atypical work schedules are somewhat prevalent in manufacturing and can degrade human performance. In a classic research, Bjerner et al. (1955) studied the number of errors through the day in relatively simple data reading tasks in an industrial context. The authors showed the effects of variation in circadian rhythms through the day on the number of errors.

In the context of this study, fatigue is simply defined as a physiological state that can potentially cause a reduction in work capacity (Grandjean 1998). This physiological state is "a biological drive for recuperative rest" and it can take several forms including sleepiness, as well as mental, physical or muscular fatigue (Williamson et al. 2011). Equally, complex manual assembly is considered to be an assembly task requiring specialized knowledge and skills for the worker to be able to execute the task. The assembled object is composed of a high number of parts with, high number of possible choices and several symmetric planes which implies increased demands on information perception and information processing (Richardson et al. 2006). The objective of this research is to understand how different practices in overtime allocation and shift management can affect fatigue among workers conducting complex manual assembly. The evaluation of potential levels of fatigue associated with these practices was conducted using the HSE Fatigue Index developed by the Health and Safety Executive (HSE) in the United Kingdom (Spencer et al. 2006).

2. Subjects and methods

Two assembly lines were considered for this study in which a total of 66 assemblers were assigned at the time of the study. They conduct mechanical assembly installing various components to the main structure of the object being assembled. Assemblers rotate between two shifts: morning shift (6h60-14h30) and evening shift (14h30-00h30). The rotation consists of three weeks in the morning shift and one week in the evening shift alternatively. Morning shifts were regular 8h shifts within a five-day work week and evening shift were 10h shifts within four-day work week. Supervisors allocate over time adding 4h blocks to shifts or adding extra workdays to the work week. The evaluation of potential levels of fatigue was conducted using the HSE Fatigue Index which allows calculating the average probability of high levels of sleepiness (Karolinska Sleepiness Score of 8 or 9) associated to a specific work schedule arrangement. Firstly, the evaluation was conducted considering the established shifts schedules to determine a baseline of Fatigue Index values. Subsequently, the evaluation was done to include practices reflecting real needs on work demands i.e., variations from the established shifts caused by overtime allocation. To simplify the analysis of real overtime allocation and scheduling we followed an approach based on the construction of common and plausible scenarios. For the calculation of the Fatigue Index different variables needed to be considered like commuting time, workload demands, type of attention and breaks intervals as well as variables related to shift work arrangement (shift length, shift start/end times, number of consecutive shifts). The latter were the main focus of the article. For this reason, when comparing scenarios, we used a methodology where we assume all of these variables to be constant (*ceteris paribus* approach) except variables related to shift work arrangement. The calculation was done using the Excel file provided by the HSE to conduct the calculation of the Fatigue Index (FI). A FI of 35 is generally considered to be a high value (Cotterill & Jones 2005).

3. Results

Results from the analysis of different scenarios of shift arrangements are presented in Table 1 and Table 2 for morning shifts and evening shifts, respectively. The last column of the tables shows the calculated Fatigue Index (FI) considering the overtime allocation associated to the shift arrangements. Of particular interest is that shift arrangement No. 6 show a real work week where a worker did 72 hours (80% more than the 40h week). This is a rare event of somehow extreme overtime but possible in practice. It was achieved by doing overtime during the week (day shift) and doing two-night shift during the weekend. Night shifts are mostly used as buffers occasionally. The calculated FI for this real shift configuration was 33.8, the highest among all the morning shift arrangements. Shift arrangement No. 1 and No. 6 correspond to normal working weeks without overtime (day shift and evening shift respectively). Their values of Fatigue Index are close: 12.9 vs. 11.5. However, for the rest of shift arrangements considering different overtime allocation strategies, results show that there is a marked difference in FI calculations. In general, evening scenarios had higher values of FI than morning scenarios of shift arrangements.

4. Discussion and conclusions

In the literature, the use of the HSE Fatigue Index has been limited to high-risk sectors in particular railroad and air traffic management (Cotterill & Jones 2005; Cebola & Kilner 2010). In the context of manufacturing, it can be useful to compare different strategies associated with shifts and working times even though this approach is not common in the domain. Our results show that FI for morning shift arrangements was little affected when the work week was extended while keeping shift length the same or whether the work week was kept the same but 4h blocks were added after the shift (16.9 vs. 15.4). In both cases the values are not too far from the baseline value of 12.9 corresponding to a normal week of morning shift arrangements. On the contrary, results indicate that evening shifts are more sensitive to the allocation of overtime to the shift. This is due to differences in lengths and time of the day (evening shift is 2h longer than the morning shift) which is aligned with fatigue build-up models reported in the literature (Spencer et al. 2006). Adding a 4h block of overtime after the evening shift has the greatest impact on FI. In all three evening shift arrangements where blocks of 4h were added after the shift, the FI were 30 or more (No. 8, No. 10 and No. 11). Ideally, to reduce the impact on FI, the 4h overtime block should be added before the normal starting time of the evening shift or at least it should be split into 2h blocks as in scenario No. 12. However, the least impact on the FI for the evening shift configurations is achieved when the work week is extended. (No. 9 vs. No. 7) The analysis presented in the study helps supervisors to consider the impact that different overtime allocation strategies have in potential levels of fatigue. This way they can make better decisions and avoid performance degradation.

Table 1. Different scenarios constructed for the morning shift and their respective Fatigue Index value**.**

Shift Arrangement	**Monday**	**Tuesday**	**Wednesday**	**Thursday**	**Friday**	**Saturday**	**Sunday**	**Fatigue Index**
1 *(Normal week without overtime)*	Start:6h30 Leave:15h00 Hours:8h	Start:6h30 Leave:15h00 Hours:8h	Start: 6h30 Leave:15h00 Hours: 8h	Start:6h30 Leave:15h00 Hours: 8h	Start:6h30 Leave:15h00 Hours:8h	Off	Off	*12.9*
2	Start:6h30 Leave:15h00 Hours:8h	Start:6h30 Leave:15h00 Hours:8h	Start:6h30 Leave:15h00 Hours:8h	Start:6h30 Leave:15h00 Hours:8h	Start:6h30 Leave:15h00 Hours:8h	Start:6h30 Leave:15h00 Hours:8h	Start:6h30 Leave:15h00 Hours:8h	*16.9*
3	Start:6h30 Leave:19h00 Hours: 12h	Start:6h30 Leave:19h00 Hours: 12h	Start:6h30 Leave:19h00 Hours: 12h	Start:6h30 Leave:19h00 Hours: 12h	Start:6h30 Leave:19h00 Hours: 12h	Off	Off	*15.4*
4	Start:6h30 Leave:19h00 Hours: 12h	Start:6h30 Leave:19h00 Hours: 12h	Start:6h30 Leave:19h00 Hours: 12h	Start:6h30 Leave:19h00 Hours: 12h	Start:6h30 Leave:19h00 Hours: 12h	Start:6h30 Leave:19h00 Hours: 12h	Start:6h30 Leave:19h00 Hours: 12h	*19.5*
5	Start:4h30 Leave:17h00 Hours: 12h	Start:4h30 Leave:17h00 Hours: 12h	Start:4h30 Leave:17h00 Hours: 12h	Start:4h30 Leave:17h00 Hours: 12h	Start:4h30 Leave:17h00 Hours: 12h	Off	Off	*23.1*
6	Start:4h30 Leave:17h00 Hours: 12h	Start:4h30 Leave:17h00 Hours: 12h	Start:4h30 Leave:17h00 Hours: 12h	Start:4h30 Leave:17h00 Hours: 12h	Start:4h30 Leave:17h00 Hours: 12h	Start:00h Leave:6h00 Hours: 6h	Start:00h Leave:6h00 Hours: 6h	*33.8*

Table 2. *Different scenarios constructed for the evening shift and their respective Fatigue Index value.*

Shift Arrangement	**Monday**	**Tuesday**	**Wednesday**	**Thursday**	**Friday**	**Saturday**	**Sunday**	**Fatigue Index**
7 *(Normal week without overtime)*	Off	Start:14h30 Leave:00h30 Hours:10h	Start:14h30 Leave:00h30 Hours:10h	Start:14h30 Leave:00h30 Hours:10h	Start:14h30 Leave:00h30 Hours:10h	Off	Off	*11.5*
8	Off	Start:14h30 Leave:00h30 Hours:10h	Start:14h30 Leave:00h30 Hours:10h	Start:14h30 Leave:04h30 Hours:14h	Start:14h30 Leave:04h30 Hours:14h	Off	Off	*30.9*
9	Off	Start:14h30 Leave:00h30 Hours:10h	Start:14h30 Leave:00h30 Hours:10h	Start:14h30 Leave:00h30 Hours:10h	Start:14h30 Leave:00h30 Hours:10h	Start:14h30 Leave:00h30 Hours:10h	Start:14h30 Leave:00h30 Hours:10h	*14.3*
10	Off	Start:14h30 Leave:04h30 Hours:14h	Start:14h30 Leave:04h30 Hours:14h	Start:14h30 Leave:04h30 Hours:14h	Start:14h30 Leave:04h30 Hours:14h	Off	Off	*34.1*
11	Off	Start:14h30 Leave:04h30 Hours:14h	Start:14h30 Leave:04h30 Hours:14h	Start:14h30 Leave:04h30 Hours:14h	Start:14h30 Leave:04h30 Hours:14h	Start:14h30 Leave:04h30 Hours:14h	Start:14h30 Leave:04h30 Hours:14h	*35*
12	Off	Start:12h30 Leave:02h30 Hours:14h	Start:12h30 Leave:02h30 Hours:14h	Start:12h30 Leave:02h30 Hours:14h	Start:12h30 Leave:02h30 Hours:14h	Off	Off	*23.4*

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