Extended Abstract: Exploring the Role of Digital Textile Microfactories in Firefighter Protective Clothing Replacement Systems under Uncertain Demand

Li Zheng
University of Stuttgart, Institute for Diversity Studies in Engineering, Pfaffenwaldring 9, 70569 Stuttgart, Germany
Tel.: +49 711 685-60703
li.zheng@ids.uni-stuttgart.de

Juan Esteban Martinez-Jaramillo
University of Stuttgart, Institute for Diversity Studies in Engineering, Pfaffenwaldring 9, 70569 Stuttgart, Germany
Tel.: +49 711 685-60702
juan.martinez@ids.uni-stuttgart.de

Meike Tilebein
University of Stuttgart, Institute for Diversity Studies in Engineering, Pfaffenwaldring 9, 70569 Stuttgart, Germany
Tel.: +49 711 685-60700
meike.tilebein@ids.uni-stuttgart.de

Jana Böhle
University of Stuttgart, Institute for Diversity Studies in Engineering, Pfaffenwaldring 9, 70569 Stuttgart, Germany
st182953@stud.uni-stuttgart.de

Alexander Mirosnicenko
Deutsche Institute für Textil- und Faserforschung Denkendorf, Körschtalstraße 26, 73770 Denkendorf, Germany
alexander.mirosnicenko@ditf.de

Keywords: Qualitative system dynamics; Supply chain management; Demand uncertainty; Inventory management; Manufacturing responsiveness

Reliable access to suitable firefighter protective clothing (FPC) is a prerequisite for safe firefighting operations. However, maintaining an adequate FPC stock is challenging because replacement needs and replenishment processes operate on different and partly uncertain timescales. On the demand side, replacement needs arise from both routine and operational causes. Routine replacement results from wear and performance degradation over the service life of the garment (McQuerry et al., 2015), while operational conditions may generate additional and less predictable replacement needs.

Replenishment is also constrained by the characteristics of the FPC supply system. FPC is a safety-critical and fit-sensitive product that relies on specialized materials and multilayer construction, limiting the possibility of rapid product substitution (Nayak et al., 2014; Song & Wang, 2019). Testing, conformity assessment, and certification requirements further restrict how easily products or suppliers can be changed at short notice (European Parliament and Council of the European Union, 2016). The supply base is relatively specialized and limited (Schiffer & Kühn, 2024), and replenishment is also shaped by formal public procurement procedures (European Parliament and Council of the European Union, 2014).

Under these conditions, FPC stock may be depleted faster than procurement, production, and delivery processes can restore it, especially when replacement demand rises unexpectedly. Shortages can therefore occur at a larger scale during periods of exceptional operational pressure or at the level of individual wearers when FPC in a suitable size is unavailable (Sokolowski et al., 2022), even when aggregate stock levels appear sufficient.

To examine these dynamics, the study adapts Sterman's (2000) generic stock-management structure to FPC replenishment and develops a qualitative stock-and-flow model. The model includes two main stocks—Available FPC and the FPC Supply Line—and distinguishes between two forms of replacement demand. Expected FPC Replacement Demand represents routine replacement needs associated with the average service life of FPC. Unexpected FPC Replacement Demand represents additional needs triggered by exceptional operational conditions, represented in the model through wildfires and other major fire events. FPC Procurement Procedure Delay affects how quickly identified replenishment needs are converted into actual orders, while FPC Production Lead Time and FPC Transport Delay affect how quickly ordered garments move through the supply line and become available for use.

The interaction of these stocks, demand drivers, and delays creates several feedback mechanisms. The model contains two balancing feedback loops. The Supply Line Control loop adjusts ordering when the actual supply line differs from the desired supply line. The Available Stock Control loop creates additional ordering pressure when available stock falls below its desired level. The model also includes two lead-time-driven reinforcing loops. In the Lead-Time-Driven Supply-Line Congestion loop, growth of the FPC Supply Line may increase replenishment lead time when production capacity becomes constrained. Slower deliveries then allow the supply line to grow further. In the Lead-Time-Driven Supply-Line Expansion loop, a longer expected replenishment lead time increases the desired supply line, which leads to additional ordering and further expansion of the supply line. Together, these loops describe how temporary shortages and delayed stock recovery may emerge under uncertain replacement demand.

DTMF capabilities are linked to specific delays in this replenishment structure. Digitalized design-to-production processes and flexible small-batch manufacturing may reduce the time required to produce replacement garments (Arfaiee et al., 2023; Winkler et al., 2022), while more distributed production may shorten the time between production and delivery (Martinez-Jaramillo & Tilebein, 2024). In the model, these effects are represented through FPC Production Lead Time and FPC Transport Delay. Shorter production and transport delays would allow the FPC Supply Line to be converted into Available FPC more quickly and could reduce supply-line accumulation and delayed stock recovery. Procurement procedures and certification requirements are modeled separately and are not assumed to be directly affected by these DTMF capabilities.

The study therefore treats FPC replacement as a delayed replenishment problem and uses a qualitative stock-and-flow model to describe the underlying dynamics. The model shows how uncertain replacement demand and replenishment delays can interact to produce temporary shortages and slow stock recovery. Linking DTMF capabilities to specific delay variables also makes it possible to examine how shorter production and transport times could affect FPC availability. Future work will further develop and evaluate the model under different demand and replenishment conditions and transfer the modeling approach to other application cases within the SysTem project.

Acknowledgment

This work was carried out in the context of the “SysTem” research project. The project, with grant number **01IF24621N**, is funded by the Federal Ministry for Economic Affairs and Energy on the basis of a resolution of the German Bundestag.

References

Arfaiee, P., Winkler, M., & Tilebein, M. (2023). Smart, sustainable and socially valuable: How digital textile microfactories can contribute to a brighter future. In J. Deuse (Ed.), *How can industrial management contribute to a brighter future?* (pp. 95–114). GITO mbH Verlag. https://doi.org/10.30844/wgab_2023_6

European Parliament and Council of the European Union. (2014). Directive 2014/24/EU of the European Parliament and of the Council of 26 February 2014 on public procurement and repealing Directive 2004/18/EC. *Official Journal of the European Union, L 94*, 65–242. https://eur-lex.europa.eu/eli/dir/2014/24/oj

European Parliament and Council of the European Union. (2016). Regulation (EU) 2016/425 of the European Parliament and of the Council of 9 March 2016 on personal protective equipment and repealing Council Directive 89/686/EEC. *Official Journal of the European Union, L 81*, 51–98. https://eur-lex.europa.eu/eli/reg/2016/425/oj/eng

Martinez-Jaramillo, J. E., & Tilebein, M. (2024). A fix that may fail: A qualitative model to explore potential rebound effects of digital textile microfactories. *Systems Research and Behavioral Science, 41*(6), 855–870. https://doi.org/10.1002/sres.3043

McQuerry, M., Klausing, S., Cotterill, D., & Easter, E. (2015). A post-use evaluation of turnout gear using NFPA 1971 standard on protective ensembles for structural firefighting and NFPA 1851 on selection, care and maintenance. *Fire Technology, 51*(5), 1149–1166. https://doi.org/10.1007/s10694-014-0446-x

Nayak, R., Houshyar, S., & Padhye, R. (2014). Recent trends and future scope in the protection and comfort of fire-fighters' personal protective clothing. *Fire Science Reviews, 3*, Article 4. https://doi.org/10.1186/s40038-014-0004-0

Schiffer, C., & Kühn, J. (2024, July 10). *Feuerwehr-Einsatzkleidung für eine sichere und vielfältige Feuerwehr* [Online training slides, DFV direkt]. Deutscher Feuerwehrverband / RWTH Aachen. https://www.feuerwehrverband.de/app/uploads/2024/07/C.-Schiffer-J.-Kuehn-PSA_Vielfalt.pdf

Sokolowski, S. L., Griffin, L., Wu, Y., McKinney, E., Morris, K., & Bettencourt, C. (2022). Examination of current U.S. female firefighting personal protective equipment (PPE) sizing and fitting process challenges: An opportunity to improve safety. *Fashion and Textiles, 9*, Article 40. https://doi.org/10.1186/s40691-022-00314-8

Song, G., & Wang, F. (Eds.). (2019). *Firefighters' clothing and equipment: Performance, protection, and comfort*. CRC Press. https://doi.org/10.1201/9780429444876

Sterman, J. D. (2000). *Business dynamics: Systems thinking and modeling for a complex world*. Irwin/McGraw-Hill.

Winkler, M., Moltenbrey, F., & Tilebein, M. (2022). Business model scenarios for digital textile microfactories. In *Proceedings of the Conference on Production Systems and Logistics (CPSL 2022)* (pp. 574–582). publish-Ing. https://doi.org/10.15488/12141