specifications. As an output, AM models are created containing all the information necessary to generate machine-readable code (CNC code). Table 3 and Table 4 present the information exchange requirements for process data and material specifications, where prerequisites are highlighted in gray.

4   Summary and conclusions

In this study, efforts towards standardizing AM data modeling have been presented, and information exchange requirements in AM have been analyzed in the context of concrete printing. The AM process for concrete printing has been defined, and information exchange requirements have been identified. Attributes within information exchange requirements for concrete printing have been collected and analyzed through a systematic review and discussion with experienced users. In conclusion, the information exchange requirements for concrete printing show synergies with the information exchange requirements of conventional AM methods. In particular for concrete printing, the hardening process of concrete has a non-negligible effect on the process parameters (e.g. manufacturing hardware settings, print strategy) and on planning and control of the manufacturing process. Therefore, the interdependencies of the concrete and the manufacturing process have to be considered along the digital thread when advancing reliability and interoperability of the concrete printing process. For illustration purposes, AM design and optimization and AM process planning have been analyzed in detail, identifying the material-related information exchange requirements necessary for concrete printing.

With the information exchange requirements clearly defined, the digital thread can be described as a formal data model. With the data model, collaboration between actors will be enhanced resulting in a smooth workflow to improve the quality of the manufacturing process and the printed components. There is still a need to develop data models that support the digital thread in concrete printing in compliance with current standards used to digitalize the AEC industry, such as open BIM standards. Through standardization, concrete printing may become a more accepted construction method in the AEC industry. Future research may therefore be conducted to further advance standardization in AM data modeling for concrete printing.

5   Acknowledgments

References

[1] ASTM International (2012). ASTM F2792-12 Standard terminology for additive manufacturing technologies. West Conshohocken, PA, United States: ASTM International.

[2] Paolini, A., Kollmannsberger, S. & Rank, E. (2019). Additive manufacturing in construction: A review on processes, applications, and digital planning methods. Additive Manufacturing, 30(2019), 100894.

[3] Buswell, R.A., Leal de Silva, W.R., Jones, S.Z. & Dirrenberger, J. (2018). 3D printing using concrete extrusion: A roadmap for research. Cement and Concrete Research, 112(2018), pp. 37-49.

[4] buildingSmart (2010). Information Delivery Manual: Guide to components and development methods. Accessed on 08/09/2021 from: https://technical.buildingsmart.org/standards/information-delivery-manual/.

[5] Kim, D.B., Witherell, P., Lu, Y. & Feng, S. (2017). Toward a digital thread and data package for metals-additive manufacturing. Smart and Sustainable Manufacturing Systems, 1(1), pp. 75-99.

[6] DIN (2019). DIN SPEC 17071:2019-12 Additive manufacturing - Requirements for quality-assured processes at additive manufacturing centers. Berlin, Germany: Beuth Verlag GmbH.

[7] Bonnard, R., Hascoët, J.-Y., Mognol, P., & Stroud, I. (2018). STEP-NC digital thread for additive manufacturing: data model, implementation and validation. International Journal of Computer Integrated Manufacturing, 31(11), pp. 1141-1160.

[8] ASTM International (2013). ISO/ASTM 52915:2020 Standard specification for additive manufacturing file format (AMF) version 1.2. West Conshohocken, PA, United States: ASTM International.

[9] 3MF Consortium (2018). 3D Manufacturing Format Specification. Accessed on 09/09/2021 from: http://www.3mf.io/.

[10] ISO (2009). ISO 6983-1:2009 Industrial automation systems and integration – Physical device control – Data model for computerized numerical controllers – Part 10: General process data. Geneva, Switzerland: ISO.

[11] ISO (2004). ISO 14649-10:2004 Automation systems and integration – Numerical control of machines - Program format and definitions of address words – Part 1: Data format for positioning, line motion and contouring control systems. Geneva, Switzerland: ISO.

[12] Buswell, R.A., Leal de Silva, W.R., Bos, F.P., Schipper, H.R., Lowke, D., Hack, N., Kloft, H.,

Mechtcherine, V., Wangler, T. & Roussel, N. (2020). A process classification framework for defining and describing digital fabrication with concrete. Cement and Concrete Research, 134(2020), 106068.

[13] Bos, F., Wolfs, R., Ahmed, Z. & Salet, T. (2016). Additive manufacturing of concrete in construction: Potentials and challenges of 3D concrete printing. Virtual and Physical Prototyping, 11(3), pp. 209-225.

[14] Wolfs, R.J.M., Bos, F.P., van Strien, E.C.F. & Salet, T.A.M. (2017). A real-time height measurement and feedback system for 3D concrete printing. In: Proceedings of the 2017 fib Symposium — High Tech Concrete: Where Technology and Engineering Meet, Maastricht, Netherlands, 06/12/2017.

[15] Kruger, J., Cho, S., Zeranka, S., Viljoen, C. & van Zijl, G. (2020). 3D concrete printer parameter optimization for high rate digital construction avoiding plastic collapse. Composites Part B: Engineering, 183(2020), 107660.

[16] Correa, F.R, (2016). Robot-oriented design for production in the context of building information modeling. In: Proceedings of the 33rd International Symposium on Automation and Robotics in Construction, Auburn, AL, USA, 07/18/2016.

[17] Mechtcherine, V., Bos, F.P., Perrot, A., Leal da Silva, W.R., Nerella, V.N., Fataei, S., Wolfs, R.J.M., Sonebi, M. & Roussel, N. (2020). Extrusion-based additive manufacturing with cement-based materials – Production steps, processes, and their underlying physics: A review. Cement and Concrete Research, 132(2020), 106037.

[18] Markin, V., Krause, M., Otto, J., Schröfl, C., & Mechtcherine, V. (2021). 3D-printing with foam concrete: From material design and testing to application and sustainability. Journal of Building Engineering, 43(2021), 102870.

[19] Wolfs, R.J.M., Bos, F.P. & Salet, T.A.M. (2018). Early age mechanical behavior of 3D printed concrete: Numerical modelling and experimental testing. Cement and Concrete Research, 106(2018), pp. 103-116.

[20] Wolfs, R.J.M., Bos, F., & Salet, T. (2019). Hardened properties of 3D printed concrete: The influence of process parameters on interlayer adhesion. Cement and Concrete Research, 119(2019), pp. 132-140.

[21] Vaitová, M., Jendele, L., & Červenka, J. (2020). 3D printing of concrete structures modeled by FEM. Solid State Phenomena, 309(2020), pp. 261-266.

[22] Roussel, N., Spangenberg, J., Wallevik, J. & Wolfs, R. (2020). Numerical simulations of concrete processing: From standard formative casting to additive manufacturing. Cement and Concrete Research, 135(2020), 106075.

[23] Perrot, A., Pierre, A., Nerella, V.N., Wolfs, R.J.M, Keita, E., Nair, S.A.O., Neithalath, N., Roussel, N. & Mechtcherine, V. (2021). From analytical methods to numerical simulations: A process engineering toolbox for 3D concrete printing. Cement and Concrete Composites, 122(2021), 104164.

[24] Kim, S., Rosen, D.W., Witherell, P. & Ko, H. (2018). A design for additive manufacturing ontology to support manufacturability analysis. In: Proceedings of the ASME 2018 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Quebec, Canada, 08/26/2018.

[25] Sanfilippo, E. M., Belkadi, F. & Bernard, A. (2019). Ontology-based knowledge representation for additive manufacturing. Computers in Industry, 109(2019), pp. 182-194.

[26] Lu, Y., Choi, S. & Witherell, P. (2015). Towards an integrated data schema design for additive manufacturing: Conceptual modeling. In: Proceedings of the ASME 2015 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Boston, MA, USA, 08/02/2015.

[27] Smarsly, K., Peralta, P., Luckey, D., Heine, S., & Ludwig, H.-M. (2020). BIM-based concrete printing. In: Proceedings of the International ICCCBE and CIB W78 Joint Conference on Computing in Civil and Building Engineering 2020. Sao Paolo, Brazil, 06/02/2020.

[28] Gradeci, K.& Labonnote, N. (2020). On the potential of integrating building information modelling (BIM) for the additive manufacturing (AM) of concrete structures. Construction Innovation, 20(3), pp. 321-343.

[29] Davtalab, O., Kazemian, A. & Khoshnevis, B. (2018). Perspectives on a BIM-integrated software platform for robotic construction through Contour Crafting. Automation in Construction, 89(2018), pp. 13-23.

[30] Peralta-Abadia, P., Heine, S., Ludwig, H.-M. & Smarsly, K. (2020). A BIM-based approach towards additive manufacturing of concrete structure. In: Proceedings of the 27th International Workshop on Intelligent Computing in Engineering (EG-ICE). Berlin, Germany, 07/01/2020.

[31] Chakravorty, D. (2020). Cura tutorial: Master Cura slicer settings. All3DP. Accessed on 09/09/2021 from: https://all3dp.com/1/cura-tutorial-software-slicer-cura-3d/.

[32] Hodgson, G., Ranellucci, A., & Moe, J. (2014). Slic3r manual. Slic3r. Accessed on 09/09/2021 from: https://manual.slic3r.org/.