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Bio-Hybrid Steerable Catheter Fabrication and Assembly within the EC 'BioMeld' Project - Part 2: Production Plan Achievement

Alessandra Caggiano[1,2,3]*, Roberto Teti[1,2]

[1]*Smart Sensing S.r.l., Naples, Italy*
[2]*Fraunhofer Joint Laboratory of Excellence on Advanced Production Technology, University of Naples Federico II, Italy*
[3]*Center for Advanced Metrological and Technological Services, University of Naples Federico II, Italy*

* Corresponding author. Tel.: +393473319319. *E-mail address:* alessandra.caggiano@unina.it

Abstract

The Biological Transformation in Manufacturing, also called as Biologicalisation in Industry, is a new paradigm fully in line with the requirements of sustainability in industrial production that allows to constructively implement novel and more effectual manufacturing technologies and systems to respond to the demands of the future generations by leveraging on the augmented employment of materials, structures and processes of living nature in production engineering with the objective of sustainable added value. To achieve these notable innovations, the convergence of biology and biotechnology, manufacturing processes and systems, and information and communication technologies is a fundamental prerequisite to provide advanced manufacturing engineering solutions for sustainability and efficiency growth. The first EC call topic on Biological Transformation "Development of technologies and devices for bio-intelligent manufacturing" was issued in June 2021 within the Horizon Europe Programme Call HORIZON-CL4-2021-DIGITAL-EMERGING-01-27, and the project proposal "A Modular Framework for Designing and Producing Bio-Hybrid Machines (BHM) - BioMeld" was submitted and approved in October 2022. This paper focuses on the 'BioMeld' project objective to develop a bio-intelligent manufacturing system for producing a bio-hybrid machine consisting of a bio-hybrid vascular catheter as innovative medical device for improved drug delivery in hard-to-access parts of the human body.

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Keywords: Bio-hybrid machine; Living cell actuator; Manufacturing system; Production plan

1. Introduction

The Biological Transformation in Manufacturing, also called Biologicalisation in Industry, is viewed in [1] as "a breaking new trend in production engineering that concurs to the pressing needs for sustainability in manufacturing and can exploit new, more effective manufacturing methods to fulfil the demands of the future generations".

A comprehensive definition of Biologicalisation in Manufacturing was proposed in [2] as the "use and integration of biological and bio-inspired principles, materials, functions, structures and resources from living nature for intelligent and sustainable manufacturing technologies and systems with the aim of achieving their full potential".

The actual implementation of the Biologicalisation in Manufacturing paradigm critically relies on the constructive and effectual convergence of biology and biotechnology, manufacturing processes and systems, and information and communication technologies to achieve the envisaged outstanding innovations in the field of advanced manufacturing engineering, comprised the substantial enhancement of production sustainability and notable progression in manufacturing operational efficiency and resource utilisation.

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2. Bio-intelligent manufacturing of bio-hybrid machines

The first EU call topic on Biological Transformation in Manufacturing entitled “Development of technologies and devices for bio-intelligent manufacturing” was published in June 2021 within the Horizon Europe Programme Call HORIZON-CL4-2021-DIGITAL-EMERGING-01-27, stating that “the use of biological elements as key enabling technology for manufacturing is an emerging trend that concurs with the pressing requirements of sustainability, and the biological transformation of industry can harness innovative and more efficient modes of production which can satisfy the needs of future generations” [3]. In response to this call topic, the project “A Modular Framework for Designing and Producing Bio-Hybrid Machines (BHM) - BioMeld“ was successfully submitted and approved in October 2022 [4].

The ‘BioMeld’ project relates to an application case of the paradigm of Biological Transformation in Manufacturing focussed on combining and integrating living materials and artificial materials to achieve greater autonomy, flexibility and energy efficiency in the realisation of a BHM consisting of a bio-hybrid vascular catheter as innovative medical device for improved drug delivery in difficult-to-reach areas of the human body compared to the present customary solutions.

The overall scope of the BioMeld project is to create a framework for BHM design and manufacturing which is applicable to the bio-hybrid vascular catheter as a case of special product manufacturing but also, more generally, to the development of further BHM instances, beyond vascular catheters, representing special product manufacturing cases.

The ‘BioMeld’ project has three principal objectives [4]:

- Establish a dependable and flexible manufacturing process for the BHM consisting of a bio-hybrid vascular catheter.
- Develop a framework of modelling and simulation for the digital design of BHM instances.
- Set up a bio-intelligent manufacturing system for the fabrication and assembly of bio-hybrid vascular catheter.

This paper concentrates on the third of the above objectives, aiming at fostering a bio-intelligent manufacturing system for the production of the bio-hybrid vascular catheter.

This manufacturing system has the joint characteristics of integrated manufacturing, where a group of organisations work together with the same industrial goal but specialize in different areas, and distributed manufacturing, where units located at different sites manufacture the product modules which are then brought together for final integration [5,6].

2.1. Bio-hybrid vascular catheter fabrication and assembly

As reported in [7], the BHM consists of a flexible, reconfigurable and modular vascular catheter with the capability for regulated flexion of the catheter tip through application of a force exerted by the contraction of muscle fibres in a bio-hybrid actuator (Fig. 1).

The catheter modules are described below and illustrated in Figs. 2-4.

- Catheter composed of three plastic tubular components.
- Bio-hybrid actuator based on muscle cell fibres action.
- Flexible electronic platform providing for the stimulation of the bio-hybrid actuator.
- Bioreactor chamber containing the muscle tissue cells immersed in nutritional fluid to stay alive and functional.

As mentioned earlier, the bio-hybrid catheter manufacturing is a case of special product manufacturing where fabrication and assembly activities are characterized by:

- Few repeated, mostly manually executed fabrication and assembly processes.
- Day-to-day activities strongly project-related and very little standardised.
- Product and process inspection procedures carried out mainly on a manual basis.
- Highly specialized operations based on multidisciplinary skills and competences.

2.2. Development of the bio-intelligent manufacturing system

A bio-intelligent manufacturing system (BIMS), comprising workstations, material handling/storage resources and control systems, is set up to perform the manufacturing processes and assembly operations required to realize the BHM consisting in a bio-hybrid vascular catheter.

The resources for the BIMS are identified and optimally selected based on the specifications for BHM catheter design and fabrication (materials, manufacturing processes, geometrical and functional features) and the BIMS is designed to be flexible in order to cope with a certain level of variation in part or product styles.

According to the concept of bio-intelligent manufacturing as defined by Byrne et al., 2021, the BIMS is established as an integrated manufacturing cell merging artificial intelligence and machine learning models with bio-inspired/bio-integrated manufacturing solutions, incorporating information channels, sensors and actuators systems.

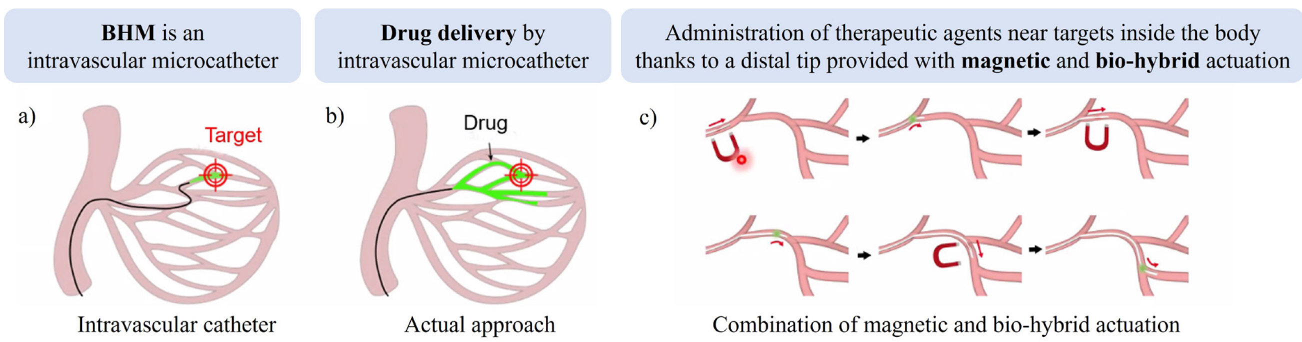

Fig. 1. The ‘BioMeld’ bio-hybrid machine (BHM) consists of a reconfigurable and modular soft steerable catheter which is flexible to produce a bending deformation depending on the force generated by living muscle cells in a bio-hybrid actuator [4].

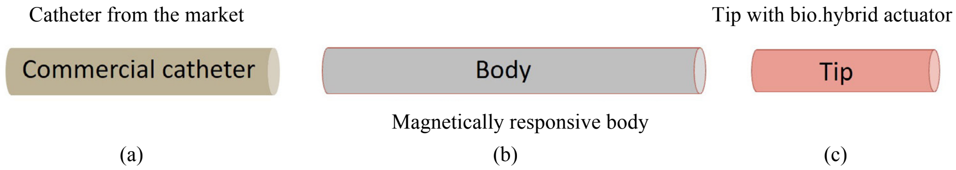

Fig. 2. Catheter made of three components: (a) commercial catheter component, (b) magnetic responsive body component; (c) soft distal tip component [4].

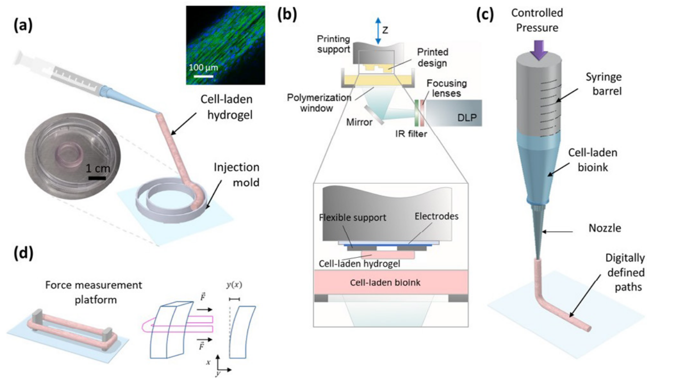

Fig. 3. Bio-fabrication processes of muscle-based bio-actuator and scheme of force measurement system: (a) mold casting; (b) extrusion-based bio-printing; (c) light-based bio-printing; (d) platform for measuring the muscle cell generated force [4].

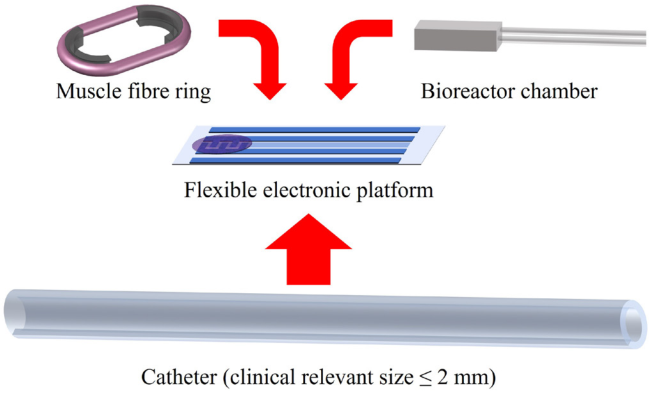

Fig. 4. Flexible electronic platform for bio-actuator stimulation and feedback from catheter distal tip motion [4].

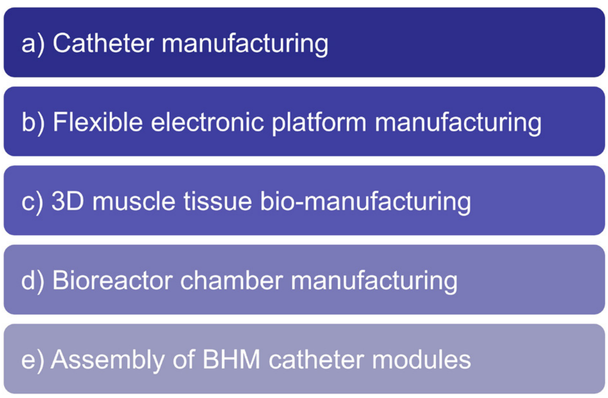

Fig. 5. Manufacturing steps for bio-hybrid catheter fabrication and assembly and their sequence in the production cycle [7].

The BIMS is expected to assess the process conditions and to autonomously apply corrective actions using data from all process chain steps, including machine and process monitoring data detected by sensors during BHM manufacturing.

2.3. Identification of bio-hybrid catheter manufacturing

The diverse manufacturing steps for bio-hybrid catheter fabrication and assembly and their sequence in the production cycle were identified as follows and specified in [7] (Fig. 5):

- Fabrication and assembly of the plastic catheter modules
- Bio-fabrication of muscle fibre-based bio-hybrid actuator.
- Fabrication and assembly of the flexible electronic platform for bio-hybrid actuator activation and real-time feedback on catheter tip motion via flexible strain sensors.
- Fabrication and assembly of bioreactor chamber to keep muscle tissue cells alive and functional in the long-term.

2.4. Survey process via tailored questionnaire

Based on the identified manufacturing steps key information for the design of the bio-hybrid catheter manufacturing system (BIMS) were identified through a survey process via tailored questionnaire submitted to the production team members to acquire, for each manufacturing step, detailed information on:

- Characteristics and design of the BHM catheter components to be manufactured.
- Identification and properties of the materials to be processed
- Definition and description of the fabrication processes, assembly operations and/or other manufacturing activities.
- Manufacturing equipment to be used.
- Inspection equipment and quality tests to be applied.
- Duration of the single manufacturing process steps.
- Evaluation of manual labour involvement in each step.
- Conditions for materials and products handling, processing and storage.
- Negative outputs that can come from inspection procedures.
- Actions to take if inspection procedures yield negative outputs (redesign, rework, recycle, reject).

2.5. Manufacturing process representation

By gathering, aggregating, analysing and interpreting the questionnaire feedback through recurrent interactions with the multi-disciplinary production team members, the survey process results allowed to develop a schematic representation of the bio-hybrid catheter fabrication and assembly activities.

On the basis of the developed scheme (Fig. 6) and further detailed inputs from the production team members, the production flow chart building was started.

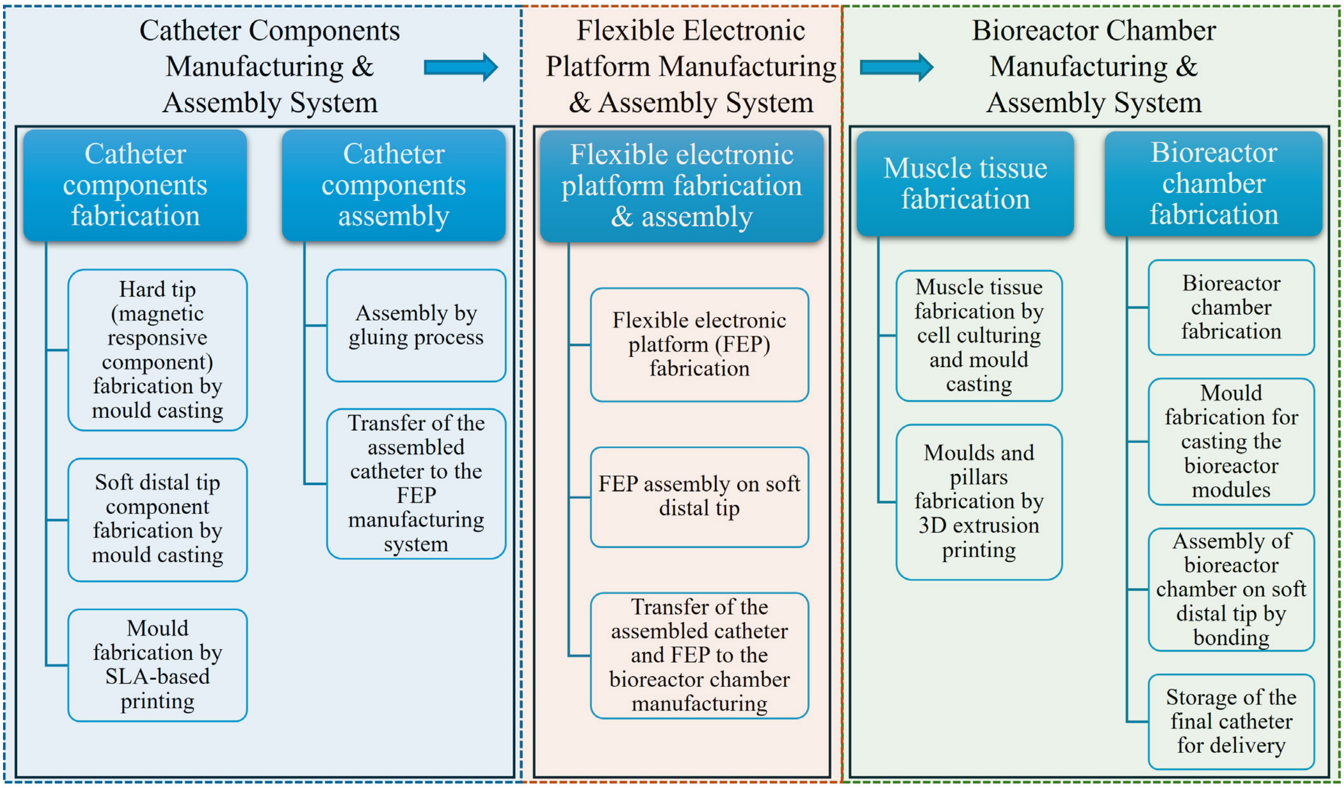

Fig. 6 – Scheme of the bio-hybrid catheter fabrication and assembly.

2.6. Construction of production flow charts

The production flow chart works as a visual tool. It is a representation that illustrates each step of a process in sequential order and is used for defining or analysing new processes, standardizing or redesigning existing processes and finding ways to improve processes by removing unnecessary steps, bottlenecks, etc.

A production flow chart is constructed with standard symbols having the following meaning (Figs. 7,8):

- An oval indicates the start or finish of a process.
- An arrow represents the direction of the process from one step to another.
- A rectangle represents a process.
- A diamond represents the decision making on an activity.
- A D-shape means delay or wait.
- A rectangle that curves up on the bottom right side means that supportive documents are required
- A rounded-edged rectangle is used as start or finish of a process

There are two types of production flow charts [8]: high-level flow chart and detailed flow chart.

The high-level production flow chart works as a macro view of the product manufacturing, focusing on the major blocks in the process; it is used mostly to identify opportunities for improvement.

The detailed production flow chart goes into greater detail providing a micro view of the activities for the product manufacturing.

2.7. Manufacturing process representation

The two types of production flow charts were constructed for the bio-hybrid catheter manufacturing.

The high-level flow chart provides a macro view of the bio-hybrid catheter manufacturing focusing on the major blocks in the production process (Fig. 7).

The detailed flow chart goes into greater detail providing a micro view of the activities for each fabrication and assembly step in the bio-hybrid catheter manufacturing (Fig. 8).

3. Next steps of the EC 'BioMeld' project activities

3.1. Production planning

The lessons learnt from the detailed production flow charts will be used to plan, manage and track the production, i.e. to set up the production planning. Production plans can be shared among production team members and when changes are required the production plan can be readily updated.

3.2. Production scheduling

Once production planning is finalised and actual production is ready to start, a production schedule will be developed, involving planning out how many units must be produced and when they should be produced. This includes allocating resources (labour, materials, machines, equipment) to each step of the production process.

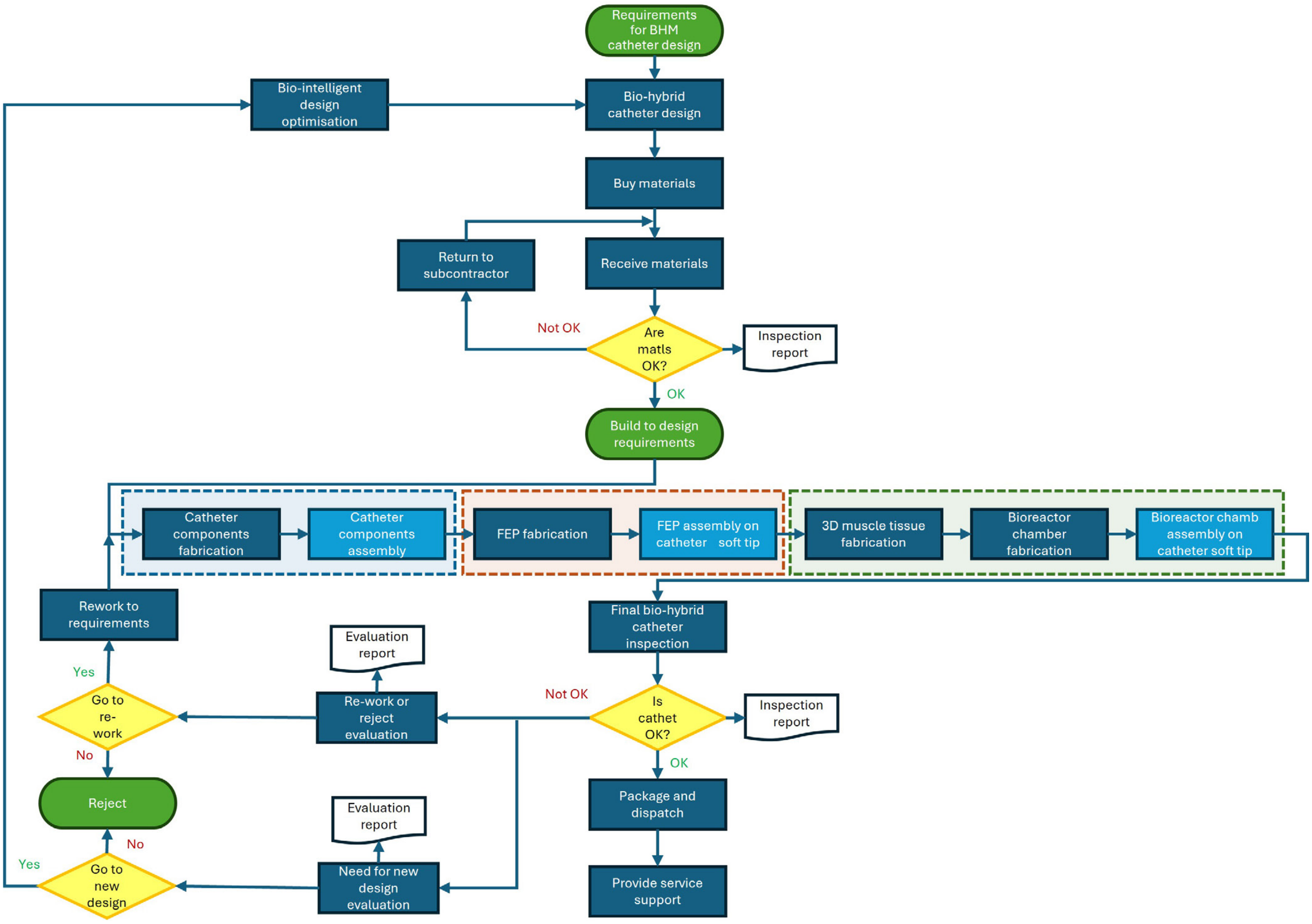

Fig. 7 – High-level production flow chart for bio-hybrid catheter manufacturing.

3.3. Design of the BIMS

On the basis of these developments, the design of the bio-intelligent manufacturing system, including the specifications and planning of the required resources and procedures, will be configured and delivered.

4. Conclusions and outlook

The Biological Transformation in Manufacturing has been defined by the European Commission as "an emerging new trend that can offer solutions to the pressing requirements of sustainability in industry" by the enhanced adoption of materials, structures and processes of living nature in manufacturing technology and systems through the convergence of biology and production engineering" [3].

The Horizon Europe project "A Modular Framework for Designing and Producing Bio-Hybrid Machines - BioMeld" submitted to HORIZON-CL4-2021-DIGITAL-EMERGING-01-27 Call 'Development of technologies and devices for bio-intelligent manufacturing' was approved in Oct. 2022 [4].

One of the principal objectives of the 'BioMeld project, relating to the development of a bio-intelligent manufacturing system to fabricate and assemble a bio-hybrid machine consisting of a bio-hybrid vascular catheter as innovative medical device for improved drug delivery in hard-to-access parts of the human body, has been the focus of this paper.

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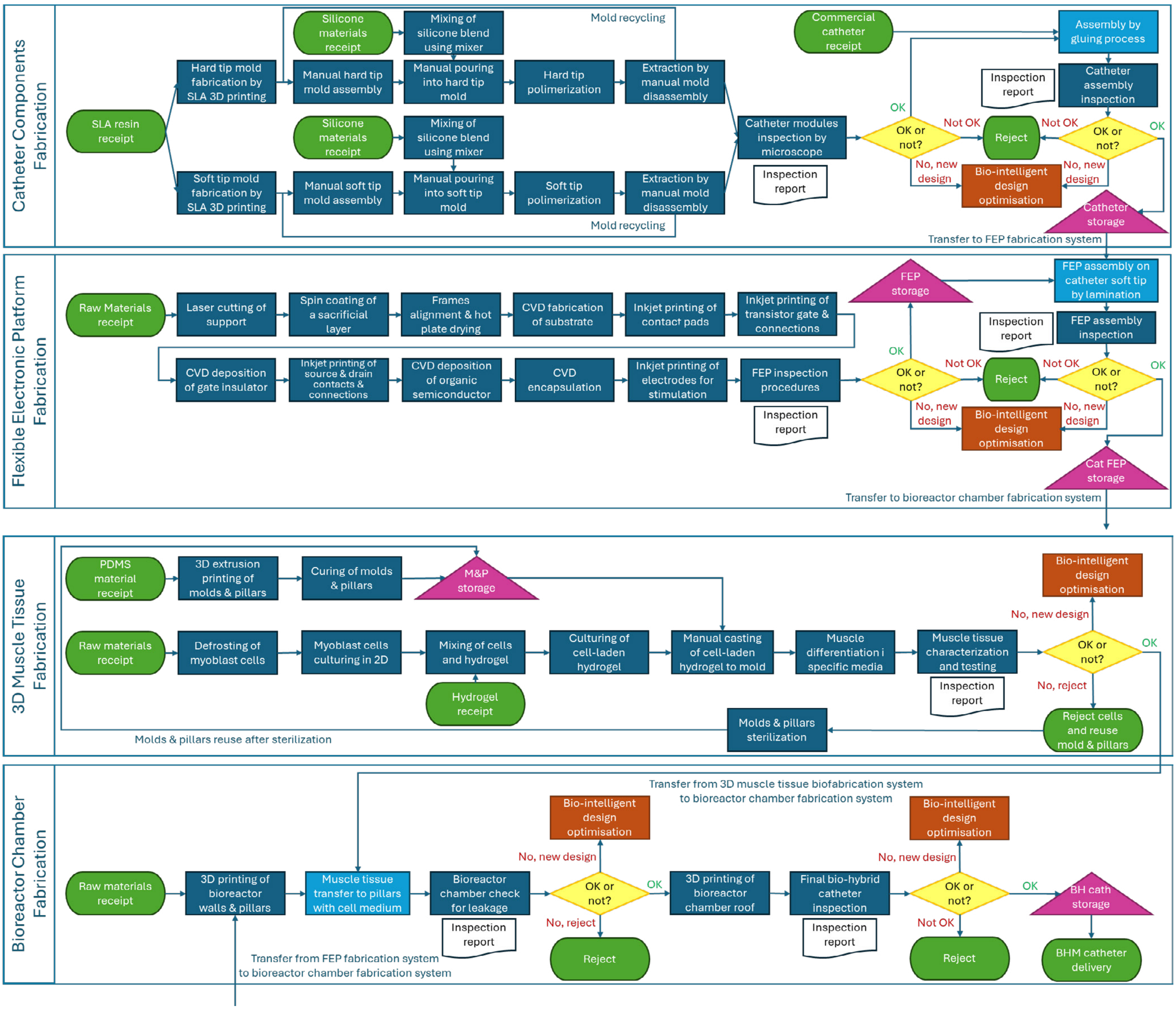

Fig. 8 – Detailed production flow charts for the fabrication and assembly of (a) catheter components, (b) flexible electronic platform, (c) 3D muscle tissue, and (d) bioreactor chamber.

References

[1] Byrne, G., Dimitrov, D., Monostori, L., van Houten, F., Teti, R., Wetrheim, R., 2018, Biologicalisation: Biological Transformation in Manufacturing, CIRP Journal of Manufacturing Science and Technology, Vol. 21: 1-32.

[2] Byrne, G., Damm, O., Monostori, L., Teti, R., van Houten, F., Wegener, K., Wertheim, R., Sammler, F., 2021, Towards high performance living manufacturing systems - A new convergence between biology and engineering, CIRP Journal of Manufacturing Science and Technology, Vol. 34: 6-21.

[3] Horizon Europe Framework Programme (HORIZON) Call Topic: Development of technologies/devices for biointelligent manufacturing, HORIZON-CL4-2021-DIGITAL-EMERGING-01-27, https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/opportunities/topic-details/horizon-cl4-2021-digital-emerging-01-27.

[4] Project "BioMeld - A Modular Framework for Designing and Producing Biohybrid Machines", HORIZON-CL4-2021-DIGITAL-EMERGING-01-27, GA No. 101070328 (2022-2025), https://biomeld.eu.

[5] Lapalus, E., Fang, S.G., Rang, C., van Gerwen, R.J., 1995, Manufacturing Integration, Computers in Industry, Vol. 27 (2): 155-165.

[6] Kühnle, H., 2010, Distributed Manufacturing: Paradigm, Concepts, Solutions and Examples. Springer.

[7] Teti, R., Caggiano, A., 2024, Bio-Hybrid Steerable Catheter Fabrication and Assembly within the EC 'BioMeld' Project - Part 1: Manufacturing Process Steps, 18th CIRP Conference on Intelligent Computation in Manufacturing Engineering - CIRP ICME '24, 10-12 July, Procedia CIRP, Elsevier, ISSN: 2212-8271, (in print).

[8] Graham, B.B., 2004, Detail process charting: speaking the language of process, John Wiley & Sons.