Deployment for Additive Construction through Digital Platforms: Gananoque Project as a Case Study

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Abstract –

This work presents the 3D Printed Construction Digital Workflow (3DPCDW) as a novel platform for integrating AEC with 3DPC, Digitalizing the 3DPC flow from basic elements to execution with robotic manipulators, while augmenting design through inherent tectonic expression of this technology. This platform was tested producing programs for the Gananoque Project, a 26 houses development in Canada by Horizon Legacy© (HL), delivering a successfully printed envelope. Thereafter, Gananoque Project positioned 3DPCDW as a foundational framework for future 3D developments.

Keywords –

Additive construction; 3D printing; automation; parametric modeling.

1 Introduction

The construction industry has seen significant technological advancements, with the integration of digitalization and automation within the framework of Industry 4.0 [1-2] conceiving a massive implementation of robotics and 3D printing[3].

In this context, Additive Manufacturing (AM) materializes a volume stacking layers by deposition, is primarily valued for its ability to enable complex designs and structural optimization [4-5]. The application of AM with cementitious materials was originally first explored by Khoshnevis [6], and it is characterized by implementation of integrating computational, 3D printing specific and material knowledge[7-9].

1.1 The Gananoque Project

The Gananoque project is a housing development consisting of two townhouse blocks of 26 houses in total. The perimeter walls of the first floor were 3D-printed, and the second storey was conventionally built with timber. For HL this project represents the first onsite proof-of-concept deployment of 3DPC.

The Gananoque project invokes a series of challenges for Digital Design Workflow (DDW), particularly on the delivery of large walls and a narrow footprint. 3DPCDW assisted successfully those challenges by retroactively interacted with 3DPC team during this early exposition to the construction site.

1.2 Digital Design Workflows

DDW's for 3DPC are parametric CAD software platforms that develop printable building data from AEC sources, principally architecture. The minimum feature is the *slicing* process, or the process of describing a 3D object into evenly displaced 2D horizontal layers along the Z-axis. At its maximum, DDW's features can become a holistic development platform, in terms of building design orientation to 3DPC, producing a *Digital Conception* of the model through parametric or generative means. These can include evaluations and simulations of all the pertinent building performances, as well as *AEC-3DPC Integration* of building geometry, material information and machinery details. This bonding of Digital Design, AEC and 3DPC Knowledge into different *Parametric Modeling* (PM) environments can potentially transform DDWs in a state-of-the-art holistic CAD platform for exploring 3DPC capability to set a new standard in buildings[11]; however, that will depend also in DDW's *Generalization* and *Flexibility* aspects in terms of scope of use and adaptation to building context vicissitudes.

Current DW use different manifestations of the BIM paradigm[12], that will tend to conventional but highly AEC-integrated development software such as *Revit®* (*BIM Systems*), and other free-form parametric CAD software such as *Rhino®* with *Grasshopper®*.

1.2.1 BIM Systems

BIM software are AEC digital tools that optimize management and collaboration in construction projects, while enhancing efficiency, reducing errors, and improving communication among key stakeholders[12]. 3DPC implementations in BIM are characterized by a powerful AEC-Integration into the design development and process, as well as a *Generalization* of the DW task because of their more robust, consolidated and construction-oriented *Parametric Objects* (PO).

Some remarkable BIM-DW include integration of the *triad*: building geometry, material information and machinery details, to produce efficient and accurate printing codes; while accessing into BIM's *Industry Foundation Classes* [8-9]. This, on the contrary of *brute-force* slicing approach, is an access to the core of BIM PO showing more integration and digitalization.

1.2.2 Free-Form Parametric CAD Approaches

Other DW systems, based on PM platforms such as *Grasshopper©*, are more suitable for producing an impact on Design Conception of the 3DPC project. This lays in their power of *Digitalization* based on the control of complex geometry and performance, through a myriad of plugins for addressing performance, interoperability with robots, etc. Nevertheless, few of the registered DWs for 3D are holistic but project-specific in terms of Design Conception. One of a few examples is Cascone et. al. that developed an entire residential multi-story building streamlining *User Mapping*, *Structural Optimization* and *Daylight Analysis* while outputting printable programs[13-14]. Other authors focus on building specific elements for 3DPC, including in their DW's Finite Element Analysis (FEA) Topology Optimization (TO) for iterate in a generative buckle that ends on 3DPC program delivery [15-16]. Breseguello et. al. using FEA for directly generate toolpath, expressing 3DPC performance-oriented tectonics [17].

2 3DPC Digital Workflow (3DPCDW)

3DPCDW is a workflow and a platform that develops building envelope walls throughout a sequence of tasks for transforming architectural geometry to 3DPC program for execution (see Figure 3), while integrating 3DPC subsystems such as pump, robot manipulator and *Wall Construction*. As a different approach from [7-9] *triad*, In the context of 3DPCDW, *Wall Construction* correspond to an AEC 3DPC Knowledge cluster that integrates constructive, structural and material variables, constraints and recipes.

2.1 Challenges for DW in the context of the Gananoque Project.

The references mentioned in the introduction set some starting positions for creating a DW. We have further acknowledged them as 5 major challenges to face and implement with 3DPCDW, to tackle the challenges of the Gananoque Project.

- **Integration:** Integrating 3DP expertise with digital design and the use of robotics in AEC. This approach minimizes manual intervention and improvisation while delivering supplementary materials efficiently.
- **Digitalization**: Effective digital representation of the 3DPC construction. Controlling the process for the digital development of walls, detailing key design features, execution phases and program delivery.
- **Generalization**: Produce a persistent and robust Workflow and Platform for future projects.
- **Flexibility**: Support for fast onsite adjustments and algorithmic adaptations when facing real contextual construction vicissitudes.
- **Digital Conception:** 3DPC powered shaping of the building project, including performance building aspects beyond 3DPC.

2.2 3DPC Systems and Subsystems comprehended

The 3D printing system implemented for the Gananoque project consists mainly of a 7thaxis manipulator called VAL 2.0 and a concrete pumping system (see Figure 1); as well as a series of diverse elements for cleaning, curing and on- the-fly editing.

Material variables such as Layer Height and Setting Time were comprehended inside Wall Construction.

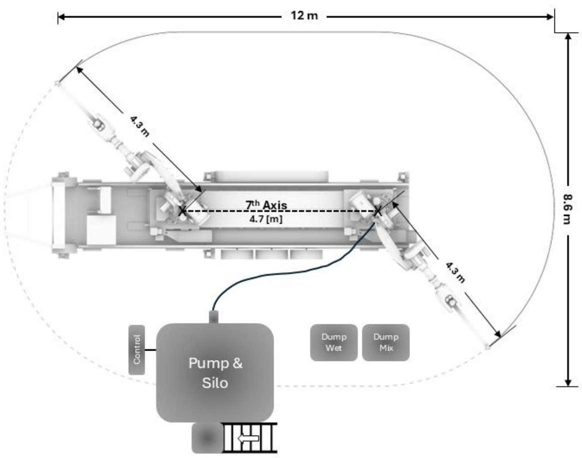

Figure 1. 3DPC System implemented in Gananoque.

2.2.1 VAL 2.0: Large AM Robotic System.

VAL 2.0 is a mobile 7-axis robotic system engineered at HL for CA, based on the ABB IRC 6700 manipulator. Gananoque's EOAT frontal reach is 4.3 [m] maximum and 3.59 [m] for wall heigh, which is amplified to a 12 [m] reach, when combined with the 4.7 [m] linear rail (see Figures 1 and 2). This enables it to execute large rows of walls by concrete and mortar deposition.

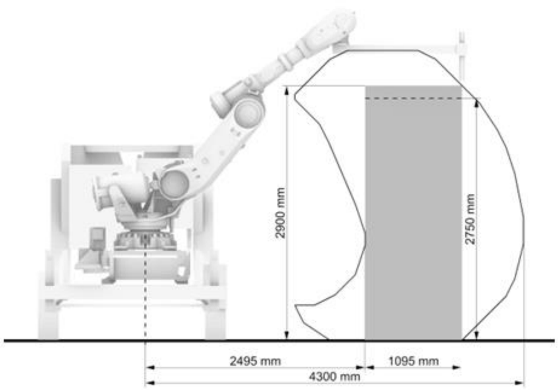

Figure 2. VAL 2.0 vertical reach.

2.2.2 Pumping System

Gananoque Project implemented a double chamber mixer specifically designed for 3DPC featuring a maximum flow of 15 [lt/min], with a 3[m^3] silo for hosting premixes., pushing a min speed of 200 [mm/sec] (see Figure 1).

2.2.3 Wall Construction

In the case of the Gananoque Project, walls consist of a complex ensemble of 3D-printed concrete and rebar, serving both as a self-supporting structure and slab interface. Two wall types were defined: W (normal wall) and *C* (corner wall).

From the perspective of 3DPCDW, wall construction is a 3DPC subsystem with integrated AEC Knowledge from the different parts involved in the Gananoque Project. It is mainly represented by 4 features:

Table 1. Features representing Wall Construction.

Wall Feature	Characteristics	Subtask
Wall Basic Morphology	Exterior, interior, lateral	Architectural Translation
Wall Segregation	Vertical segregation	Toolpath Programming
Wall Complements	Rebars and other structural components	Architectural Translation
Wall Pattern Allocation	Perimeter Projection	Wall Tectonics

3 Digital Workflow

3.1 Architectural Drawing Translation:

The architectural project is initially integrated by processing 2D wall outlines in accordance to *Wall Basic Morphology* to create *Primitive Wall Objects* (PWO). It also generates plans deriving knowledge from *Wall Complements.*

PWOs further simplify wall programming and serve as an interface for future 3DPCDW versions to receive and process other architectural projects.

3.2 3DPC Programming Tectonics

3.2.1 Wall Tectonics

This task augments architectural walls by exploring tectonics unique to 3DPC building components, enabling the Gananoque Project to showcase 3DPC's material expressiveness and structural potentials. As a limited augmentation, it only modifies the projection of the main wythe or the faces of the walls.

Wall Tectonics take the *Perimeter Selection* from the PWOs to add *Wall Patterns* with *Maximum Projection*. This proceeds directly onto toolpath layers as *polylines*, offering more accurate control over the target number economy and enhancing the control of 3DPC tectonic features.

In detail, *Wall Patterns* consist of the allocation of a certain 3D *Relief Pattern* and an associated *Dripping Pattern*. A relief pattern is defined as a volume projected from a supporting background, while a dripping pattern is a tectonic feature that uses a detour at the wythe's intermediate layers with extra peak-point projection, utilizing gravity for the controlled falling of material. The wall pattern modifies this façade gradually, with a maximum nominal value of 55mm to 75mm for wall relief projection, and a 15mm extra projection for dripping patterns. As options, these patterns can create different conjugations or types: *NN* (no pattern), *TN* (wall with relief), *NT* (wall with dripping), *TT* (wall with relief and dripping), that can be suitable for other projects.

3.2.2 Toolpath Designing

This step implements Wall Construction's *Wall Segregation* recipes, defining the suitable toolpath strategies and creating various toolpath types. Toolpath features such as types are essential in programming 3DPC tasks, as they align with the 3DPC system's actual capabilities and limitations, to enhance productivity. They allow for the printing of large amounts of walls and tool changes during the print process.

From this process 3DPCDW delivers four toolpath types: *Sp* (simple print), *Gp* (group print), *DtSp* (double tool simple print) and *DtGp* (double tool group print), according to current *Selected Walls*. While these strategies offer positive effects, they also introduce complexity and require more control during the print process.

3.3 Toolpath Intervention and Diagnostics

This subtask will evaluate printing programs against VAL 2.0 position for manipulator reaching and printing variables compliance, leading to *Program Delivery*, or requesting changes in previous subtasks such as *Toolpath Designing* or rejecting a current wall group.

This is relevant because it ensures and details reachability, while achieving stable speed that are critical for maintaining precision and quality during printing.

3.3.1 VAL 2.0 Allocation and Movement Control

This subtask will evaluate toolpaths into context, for manipulator reaching, correct movement and printing variable compliance. It consists of an automatic or interactive simulation buckle that allocates the VAL 2.0 for reaching target walls and, if necessary, produce tool rotations for adapting VAL 2.0 range, enabling the inclusion and printing of perpendicular wall parts without collision. If this is still unsuccessful, changes in wall grouping and spilling locations need to be made.

3.3.2 Toolpath Analysis

This step delivers a diverse set of diagrams (see Table 2.) to verify wall and program integrity, along with recommendations for appropriate variable ranges. It serves both the 3DPCDW user and robot technician for identifying potential issues that could disrupt the manipulator's smooth movement and affect quality.

Table 2. Different *diagram* reports for code analysis.

Diagram	Description
Code Speeds	Controls bead width, avoid bulkiness.
Zone Values	Sharpness and aesthetic patterns.
Setting Times	Diagrammed for each layer, section (*feet*) and walls.
Rotation vs. Length	Gradients for speed issues from 6th Axis rotation coordination.
Code Parts and Segregation	Program compliance regarding location, start, finish, and *robotStops* for the whole task.

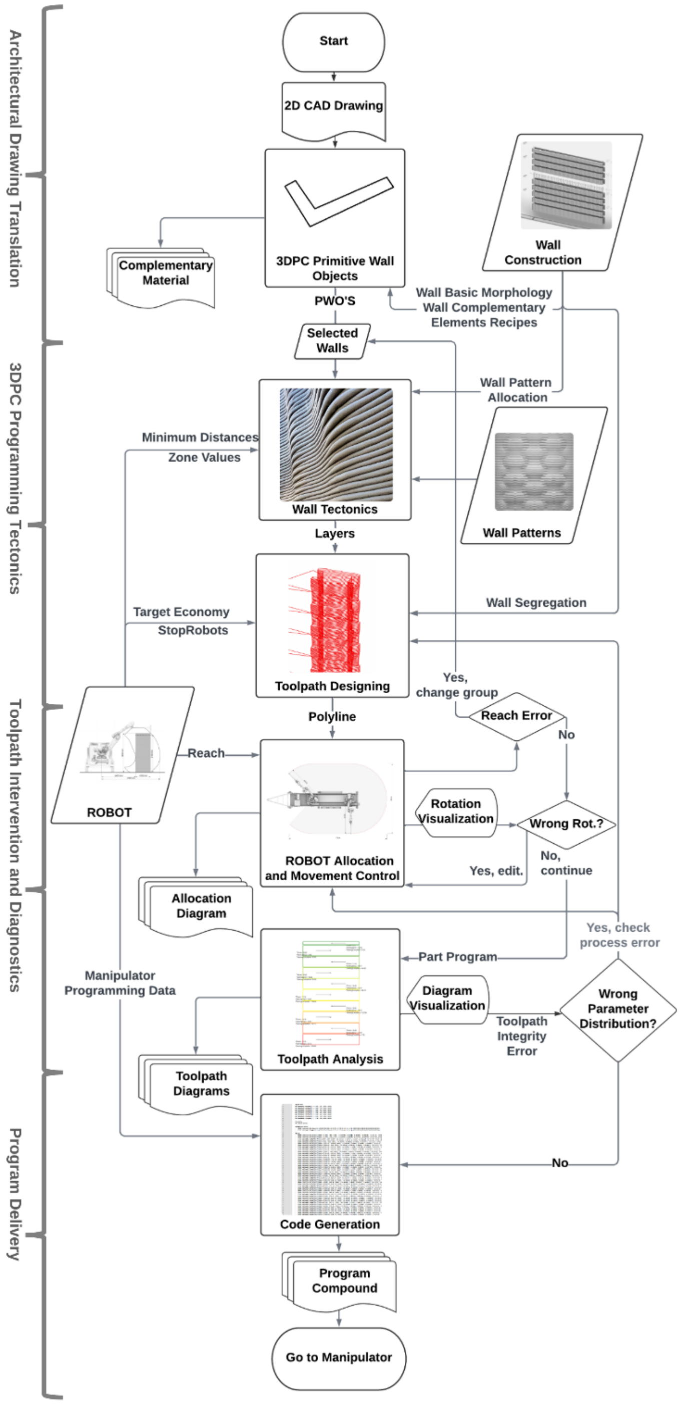

Figure 3. 3DPCDW structure.

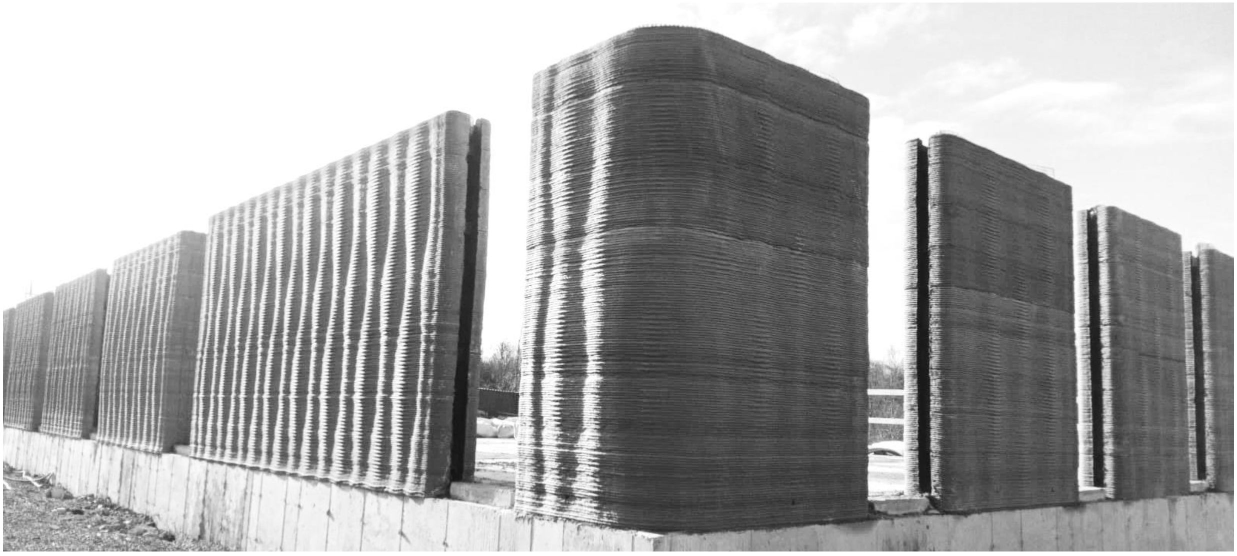

Figure 4. Perspective view of 3DPC Walls.

3.4 Program Delivery

This task generates a *Program Compound* consisting of 4 codes for completing a 3DP task through pre-evaluation and printing; first one consists of *Dry-run* and *Probe* programs that enable the robot technician to ensure material and printing task program compliance respectively, where the second one executes the actual printing task (see Table 3).

Table 3. Content of a *Program Compound* delivered by 3DPCDW.

Type	Description
Main	Main routine, for running program parts.
Part	Program part, involving total or a wall(s) portion modulated by sections.
Dry-run	Dry-run file for program compliance through simulation.
Probe	Program with different probe shapes for structural testing.

4 Results

A total of 25 walls were produced to host 26 townhouses in Gananoque. These walls included both straight and corner walls. Results are addressed in terms of: Preparation, Printing Task and Printed Results.

4.1 Preparation: Digital 3DPCDW Outcomes

There were effectively 19 program compounds required to complete the 25 3DPC walls of the project, specifically: {*StSp*=9, *StGp*=2, *DtSp*=4, *DtGp*=8}, Notably *StSp* prints were preferred in the last month due to the capabilities achieved, practicality and compatibility to the period mix. The main task was employed exclusively on prototyping, while the probe was used in 1 of every 5 prints. *Dry-run* and *Parts* were always used.

4.1.1 3DPC as a Platform

As a platform, there were several updated versions (20) of the 3DPDW, most of which were actualized on site during a prototyping period prior to actual printing. This was critical because of unforeseen situations, such as accommodation of slab and key tolerances, quality concerns and integration of observations that enhanced execution. The tasks were represented by:

- **Integration:** AEC Integration through Wall Construction.
- **Digitalization:** Wall to 3DPC program. Representation subtasks.
- **Generalization:** Through Parametric Wall Objects (PWO), the production of wall and group programs.
- **Flexibility:** Through 3DPCDW parametric interaction, ease of 3DPCDW and algorithm edition.
- **Design Conception:** Through Wall Design Augmentation and PWO compliance, generative building envelope solutions can be produced.

Program versioning (20) represented critical modifications of 3DPCW mostly before the definitive printing period. These involved, for example, adding multi tool capabilities, toolpath adaptation to fit the key, including *probe* in program compound, etc. Other non-vital complements such as adding more *diagrams* to

Toolpath Intervention and Diagnostics were made in parallel on the definitive print period. Second half of the definitive period only required parametric change.

4.2 Printing Task

Changes in wall grouping and allocation from previous codes were necessary for executing the 3DPC task, mainly due to alterations in the printing sequence, which were constrained by confronting the slab and VAL 2.0 possible movement ranges while moving.

Code reaching errors were found where tolerance with actual project were more than 10 mm from the actual VAL2.0 position. This happened typically on large wall groups where maximum reach was needed.

Changing pattern parameters was necessary when changed mix between Block 1 and Block 2, reducing wall pattern projection.

4.2.1 3D Printing Task

The Printing task integrates 3DPCDW digitalization. Numbers 4 to 7 are repeated 9 times to get an actual height of 2.75 [m] (see Table 4.):

Table 4. 3D Printing Subtasks.

#	3DP Subtask	3DPCDW Related Output
1	Pump preparation	-
2	Calibration & *Dry-run*	*Alloc. Diagram* *Probe* *Dry-run*
3	Material setup	-
4	Printing 1 feet high	*Part*
5	Change of wall or stop	*Part/robotStop*
6	Install rebar compound	*RebarDiagram*
7	Continue printing next wall or next feet	*Part*
8	Stop printing	*Part/robotStop*
9	watering & covering	-
10	Pump cleaning	-
11	Move into next position or close	*Alloc.Diagram*

- **2:** Calibration and Dry-run time. This 3DP task demanded a few program compound modifications.
- **6:** Installing rebar compound. The *Rebar Diagram* gave correct dimensions for rebar cutting and positioning, while considering high tolerances
- **7:** As printing tasks consisted of many *parts*, loading of next program part, on stop robot location. No considerable time was expended from *part*-to-part loading.
- **11:** Robot allocation was made using the *Allocation Diagram*, where differences of less than 10mm were admitted. Time here was considerably high (10 mins min, 1 hour max) especially when going out of the wall row.

4.2.2 Material Waste

Material waste for group prints (*DtGp* and *StSp*) toolpath strategy waste less material, because of the alternation between walls eliminates waiting spilling time. In the case of individual wall printings, robot stops in spillage zones produced waste while waiting on rebar allocation. Results on material use show an average of 15% of material loss.

4.3 Printed Results

4.3.1 Global Dimensional Results

Walls exhibit rough compliance with length and width measurements, with the majority closely matching the required dimensions, resulting in deviations of 0 to 20mm. These results depend on many factors, non standing changes from Block1 to Block2 established significant difference.

4.3.2 Dimensional Results on Beads

Bead widths show some variation but remain within acceptable tolerances. Although the centres were conceived to be 75 mm ± 5 mm, tolerances can go up to 100 mm because of the *Dripping Pattern*. The wall width and side beads were designed to be 85 ± 5 mm; however, the maximum use of the rail increased the bead width because of speed dampening effects.

4.3.3 Aesthetic Results

Aesthetic results were found expressive, with clear Design Pattern gradients for the *Relief* and *Dripping Patterns*. Different mixes yielded different surface finishes, so a lower Projection Parameter for Relief and Dripping was counterweighted with harsher texture, and softer surface finishes were expressed better with a more higher *Projection Parameter* value (see Figure 6).

5 Discussion

3DPC Task execution is highly complex and relays mostly on implicit *knowhow* of the professionals involved [18], so 3DPCDW made a great part of this *knowhow* explicit, integrated and functional.

As 3DPCDW also increased its capabilities over time, retrofitting from the context and then be just operated by parameter change, its *Flexibility* and *Generalization* effectively supported Gananoque Project linkage between materiality by means of *Wall Construction*, design and robotics.

Figure 5. Perspective detail view of 3DPC Walls.

5.1 Printing Task Discontinuity and Times

Regarding times expended in the Printing Task, less than 60% is used on the actual 3D print (see Table 4). Number 1 to 3 and 9 to 11 require up to 40% of the Printing Task. There is some potential in automation of subtask 2 and 11 that require more than the 20% of the Printing Task. On both (2 and 11), the use of diagrams and analogue measurements were performed. What was expressed through diagrams in Gananoque may be automated in the future for a more productive performance. Implementation of *Computer Vision* (CV), positioning automation and other technologies such as *Digital Twins* can be implemented for efficiency, however, what's closer to implement depends on multiple factors.

Printing task discontinuity is not desirable. The two major factors are individual prints execution and rebar positioning, both of which are related. The first one can be tackled by printing only wall groups, however changes in mixing setting time expressed bulking, especially in short walls (see Results: Printed Result). The second factor can be solved by robotic *on the fly* rebar positioning or using better rebar design.

5.2 Printed Results Discussion

Results on material use show a general 15% of material loss. This is almost equivalent to constructing four new walls of 3 mt, including losses. A major amount of this material waste can be mitigated through enabling group printing on 3DPCDW, however, this is caused by the pump's inability to produce extrusion stops.

Another pump enhancement regarding quality issues is the coordination with robot speed, or its control directly by the robot program, for solving vertical bulkiness and horizontal extrusion variations.

6 Conclusion

We presented a platform for creating 3D- printed envelopes by means of Automation of 3DPC. The actual successful implementation of this was demonstrated through the printing of the Gananoque project´s wall units. Raising the technological level will hopefully increase 3DPC team and tasks productivity, producing also more precise and cost-effective products.

PM offer precise control over project walls, enabling unique tectonic expressions through toolpath strategies based on 3DPC knowledge. Insights into manipulator rotations and controlled material falls can enrich 3DPC oriented design by shifting the focus from representation to generation, challenging traditional design approaches.

Generalization, through using both persistent geometry and workflow, enables 3DPCDW with the ability for solving a wide range forthcoming 3D projects. Increment in wall object intelligence regarding performative and practical 3DPC oriented design must keep *Flexibility* of 3DPCDW.

3DPCDW Design Conception missed generative means that are ageless on CAD culture, however, less conventional shapes in architectural design weren't possible until *Digital Fabrication* and 3DPC arrived. Frameworks and the notion of *Design Spaces* for exploration linked with actual predictive performance of the 3DPC physical phenomena can empower different and more interesting architectural spaces, 3DPC tectonics, building performance, ergonomics and other explorative but useful built expressions.

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