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Design for manufacture and assembly (DfMA) enablers for offsite interior design and construction

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Abstract

Interior design and construction (IDC) is a sophisticated and often prolonged process thatdelivers a building to occupation. Traditional practice is rather unproductive, involving thework of several different trades crowded in situ and delivered sequentially one after another.To enhance productivity in IDC, offsite practice is receiving increasing attention as a processinnovationalongwithDesignforManufactureandAssembly(DfMA),anemergingconceptinthe industry. This paper aims to investigate offsite IDC practice and develop a set of DfMAenablersforbetterachievingthisbuildingprocess.Itundertakesaliteraturereview,casestudy,and 18semi-structuredinterviews.TosupporttheoffsiteIDCanditsproductionline,standardizedprocedure,automatedmachinery,andsupplychain,10DfMAenablersareadopted, suchasearly collaboration,designstandardization andsimplification,and lightmaterialselection.Thesefindingsindicateaparadigmshiftnotonlyininteriordesignmethodologybutalsoin IDCprofessionalpracticeprocess.Thisresearchenrichestheliteratureon DfMA and IDC, in particular their synergy, and offers a new model for interior designersandoffsiteIDC practitioners.

Keywords: DesignforManufactureandAssembly;Enablers;Interiordesignandconstruction;Offsiteconstruction.

Introduction

In the building industry, an 'interior' refers to the internal space of a building structure ormicroscalehuman-madeenvironment(Ching&Binggeli,2018;Harwood,1991).Designofaninterior is a challenging undertaking because it has an immediate effect on the wellness,physicalandmentalhealth,andproductivityofitsusers(Evans,2003;Ulrich,1991).Designersmust consider an array of factors, including regulations, mood and tone, decorative styles,spatialplanning,construction,materials, indoorenvironment,andsustainability(Friedmann&Savage,2020).Likewise,interiorconstructionisnotoriouslycomplicatedandtime-consuming.Before a building can be occupied, the work of several trades must be completed, such asflooring,partitioning,finishing,heating,ventilation,airconditioning(HVAC),andmechanical,electrical, and plumbing (MEP) installation. Traditional practice depends heavily on in

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situconstruction,whichislabourintensiveando ftendonewithoutastandardizedworkingproced ure (Jaillon& Poon, 2008). Among all aspects of project delivery, including foundationandsuperstructureerection,interior designandconstruction(IDC)isusuallythemost onerous,causing project delays, errors and reworks, workforce safety risks, poor constructability, andlossofproductivity(Friedmann&Savage, 2020).
Inspiredbytheprojectmanagementtechniques ofcrashingandfasttracking(Ballesteros-Perezet al., 2019) and prefabrication construction (Gibb, 1999), the nascent area of offsite IDC(whichmayalsobereferredtoasprefabricat edIDC)isreceivingincreasingattention,particu larlyinrepetitivehigh-risebuildingprojects.Whilethesuperstructurei sundererection,IDCcanbeperformedinanoffsi teplace(e.g.,afactory)inparallel.Theinteriorel ementssuchas flooring, partitioning, finishing, and HVAC are designed in modules and prefabricated.Offsite IDC moves many construction activities from a site to a manufacturing line, providinga factory-like working environment and enabling mass production in the industry. It alsosignificantly reduces wet trades and potential crowding of labour onsite. For these reasons,many industry practitioners and scholars consider offsite IDC to be an important processinnovationinbuildingprojectdelivery(DEVB,2018).Italsopresentssignificantopport unitiesandchallenges forDesign forManufacture and Assembly(DfMA).

DfMA is ‘both a philosophy and a methodology whereby products are designed in a way thatis as amenable as possible for downstream manufacturing and assembly’ (Gao et al., 2020).Originated from the manufacturing industry, DfMA has been applied to many sectors, such asautomotive(Sureshetal.,2016),aerospace(R ajamani&Punna,2020),andconsumerproducts (Boothroyd,1994).Recently,somearchitectura l,engineering,andconstruction(AEC)organiza tions have begun to adopt this emerging design thinking to unlock value for clients.DfMA, sometimes regarded as a ‘buddy system’ of prefabricated construction, offers a newway to meet the demand for mass, efficient, and high-quality production (Tan et al., 2020).VariousstudieshaveexploredDfMA enablersintheAECindustry.Here,adesignenab lerisatool,technique,orstrategythatassistsdesi gnersatvariousphasesofthedesigncycleandcan

beassimpleasarequirementschecklistorascomplexasacustomizedcomputer-basedanalysistool(Kayyar,2007).IntheAECindustry,DfMAenablersincludetransformationanddevelopmentof the industry (Gaoetal.,2020),understanding ofprojectconditionsandconstructionprocess(Tanetal.,2020),digitalization(Yuanetal.,2018), governmentlegislationandincentives (Gao etal.,2018), anddesignoptimization (Gerthetal.,2013).

However,mostDfMAenablers,instructions,andframeworksarebasedonarchitecturaldesignand construction, with little consideration, if any, of IDC. Differences in the design andassembly phases of architectural and interior design mean that construction-oriented DfMAenablers are not necessarily applicable to interior design scenarios. The DfMA enablers fromoffsiteIDCpracticeremainunexplored.Moreover,theinvestigationofmodernoffsiteconstructionhasbeenmainlyundertakenbythearchitectureandcivilengineeringcommunities.There is almost no research on prefabricated design and construction for indoor environments(Schneiderman,2011).

Tofulfilthisgapandmaximizethevalueofthisinnovativebuildingprocess,thisstudyaimstoinvestigate offsite IDC practice and develop a set of DfMA enablers. It adopted qualitativeapproachesinvolving areal-life casestudy, 18semi-structured interviewsand asitevisit.

Interiordesignandconstruction

Interiordesignandconstruction(IDC)isacreativeandcoordinatedmethodologyusedtodesignand construct interior and microscale environments that improve quality of life, productivity,health, safety, and welfare (Ching&Binggeli, 2018; Harwood, 1991). It primarily emphasizesvarious details, such as space planning, furniture arrangement, interior surface treatments,fixtures, colour and tone, finishing materials, lighting, electrical and communication system,graphics, and signage. Compared to architectural design and construction, IDC is perceived tobe more ‘feminine’, ‘artistic’, and ‘detailed’ (Havenhand, 2004). It is often a subsystem ofprojectsthattakesplaceafterarchitecturaldesignandbuildingconstruction(Havenhand,2004).Thisuniqueprofessionrequiresspecialqualificationsandhasitsown setofprinciples,knowledge,criteria,standards, andorganizations.Italsohasamassiveimpactonorisimpactedbytheactivitiessuchasmaterialprocessing,production,assembly,occupancy,renovation,anddemolition(FIDER, 1988;Harwood, 1991).

Recently, the influence of offsite construction technology has begun to be seen in IDC. Whiletraditionalmethodsheavilyrelyononsiteactivitiessuchaswetprocessingandcuttingmaterialstofitavailablespace,offsiteIDCtransfersaportionofinsituworkstoafactory-likeenvironmenttoallowmassproduction(Jaillon&Poon,2008).Itcanbeconsideredaninnovative construction practice, involving pre-assembly of components in a manufacturingline and then transportation of these components to the site where the structure is located(DEVB,2018;Gibb,2001).Thisshiftinstigatesmanyadvantagestotheindustry,includingan

escalationinconstructionproductivityandsafety(Jaillon&Poon,2008).However,theachievementofoffsiteIDCrequiresstrongsupportandchangeinthetraditionalIDCprofessionalpractice.Theinteriordesignprocessholdsaprodigiousopportunitytosupportthisconstructiontechnologyfromtheearlystageofabuildinglifecycle,butthe implementationofDfMAininteriordesignfirst needstobereinterpretedandcontextualized.Thus,explorationofDfMAenablers forIDC is a pressingneed.

DfMAinconstruction

DfMAwasintroducedinthemanufacturingindustryundertheumbrellaofDesignforExcellence (DfX), where 'X' or 'Excellence' can be substituted by many terms to mitigatevarious challenges (Kuo et al., 2001), e.g., Design for Environment (DfE), Design for Safety(DfS), and Design for Construction Waste Minimization (DfCWM) (Laovisutthichai et al.,2020).Thisdoctrinehasbeenreinterpretedandadoptedbytheautomotive(Sureshetal.,2016) andaerospaceindustries(Rajamani&Punna,2020),amongothers.IntheAECindustry,DfMAcanbedefinedas:(1)adesignprocessandprinciplesforapproachestostructuralorcomponentmanufacturingandassembly;(2)adesignevaluationsystemformanufacturabilityandassemblability;and(3)adesignphilosophyembracingprefabricatedconstructiontechnologies(Gao et al., 2020). To promote DfMA in the AEC industry, numerous DfMA enablers havebeeninvestigatedandproposed.Aftersearching databasesandscrutinizing the collectedfindings,wehavecompiledalistof10DfMAenablersforarchitecturaldesign,shownin Table1 withexplanations.

Table1.DfMA enablersforarchitecturaldesignfromtheliterature

These DfMA enablers help remedy discontinuity and fragmentation in the AEC industry bybreaking 'the wall' between designer and manufacturer (Boothroyd, 1994). Other advantagesincludesavingsintimeandcosts,processsimplification,labourforcesafety,andimprovementsin constructability. However, it can be seen from Table 1 that these lessons are mainly derivedfromthearchitecturalandstructuraldesigncases.DfMAenablersforIDC,includingfinishing,MEP,and HVAC designand construction, arerarelyinvestigated.

Researchmethods

The study adopts a series of qualitative research approaches, combining interviews and a sitevisit organized as single case study. A case study allows researchers to focus on a particularissue,featureorunitofanalysistocomprehendcomplexreal-lifeactivities(Croweetal.,2011;Noor,2008).Itisoftenjointlyusedwithotherqualitativemethodstoenhancerobustness(Yin,2017;Baoetal.,2019).Inthisstudy,byexaminingthecaseofoneofthelargestIDCcompaniesin China, we aim to develop a set of DfMA enablers that are of immediate use and potentialreferentialvalueto interior designersandother interested parties.

Casedescription

The case study firm has undertaken a series of IDC projects and built a reputation around theglobe.ItistheIDCproviderforalmostallwell-knownhotelmanagementgroups.Foragreenerandsmarter IDC industry, inrecentyears,thefirmhaspioneeredthepromotionofprefabricatedIDC.Thefirmhasdevelopedarelativelymaturesystemforprefabricated IDC, whichhasbeenimplementedinseveralreal-lifeprojects.GivenitsprominenceintheoffsiteIDCbusinessbothinChinaand overseas,weexpect to derivesufficient insights from our casestudyofthis firm.

Interviews

To garner insights into DfMA for prefabricated IDC, the authors conducted a series of semi-structuredinterviewswithstakeholders inthecasestudyfirm.Asemi-structuredinterviewisaqualitativeresearchmethodwhereinterviewees areusuallyaskedaseries ofpredetermined,butopen-endedquestions(Given,2008).Itisparticularly usefulwheretheopinionsandperceptions of interviewees on complex issues are sought (McIntosh and Morse, 2015), and isthus considered a suitable method for teasing out insights on DfMA for prefabricated IDC. Intotal,18semi-structuredinterviewswereconductedoveratwo-monthperiod.Basicprofilesoftheinterviewees areshowninTable2.Selectionofinterviewees wasbasedontwocriteria.Onewastheexperiencein IDCandpracticalinvolvementinatleastonephaseofprefabricatedIDC.For a rounded picture, the other was a sufficient diversity of interviewee backgrounds to coverdifferent phases of IDC. All semi-structured interviews were conducted face-to-face to allowforanintuitiveapproachandtheopportunitytoelicitmorein-depthinformation.Sincethegoalofdata saturation was accomplished, theywereconsidered satisfactoryforthis study.

Table2.Basicprofilesofinterviewees

Interviewswereconductedintworounds.Duringthefirstround,thequestionsweremoreopen-ended. In the second round, with reference to the 10 DfMA enablers identified by the authors(see Table 1), interviewees were asked whether they had adopted any strategies in their designprocess. If yes, they were asked to describe each strategy and operation in detail. To minimizebias in interviewees' opinions, the authors used objective questions to elicit factual responsesrather than subjective personal opinions. Given the potential for DfMA enablers beyond thosepreviously identified by us, flexibility was provided for interviewees to discuss additionalDfMA strategies used in their practice, if any. Each interview lasted between 1 and 1.5 hoursand was audio-recorded with interviewees' informed consent. All recordings were transcribed,andlabelledbyintervieweename.Duringtranscription,theauthorscontactedsomeinterviewees againthroughtelephonetoverifyanddclarifyvagueinformation.After18transcription documents were produced, DfMA enablers for interior design mentioned by themajority,i.e.,two-thirdsofinterviewees,werenoted.Atleasttwoauthorswereinvolvedintheconduct of interviews and interpretation of the transcribed documents to ensure transparencyandminimize biasintheresults.Further,allauthorscouldaccesthe transcriptsandcomment

andrevisethedataanalyses,anapproachsimilartoenhancinginter-raterreliability.

Sitevisit

Thesitevisitwasundertakentodeepenourunderstandingofhow DfMAenablersareexecutedand reflected in real-life prefabricated projects and inform our interpretation of the interviewresults. Sample prefabricated interior projects that the case study firm showcases to customerswere viewed, mainly to observe differences between the appearances of prefabricated IDCprojects (see Figure 1) and conventional IDC projects. The site visit took about two hours, andthe project manager accompanied the authors and elaborated on how these prefabricated IDCprojectsareconducted usingdifferent construction technologies.

Figure1.Buildinginteriorscompletedusingoffsite IDC

Results

The case studyandinterviewresults,basedonthecriterion of interviewee mention frequency, supportthe formation ofDfMAenablers foroffsiteIDC (seeTable 3).

Table3. Asummaryof DfMAenablersforoffsiteinteriordesignandconstruction

Collaborativedesignwithearlyengagementwitharchitect

The emergence of offsite interior construction suggests that interior design should be involvedat a very early stage to better synchronize with the architectural design. At a very early stage,architects are strongly suggested to consider many offsite IDC factors such as the standarddimensionsof prefabricatedinteriormodules.Interviewee11explained:

Thewidthanddepth ofaroom areencouragedtobetter fitintothe dimensions(bestinanintegralmultiple)of somemost commonlyadopted modules in theinteriordesign.

However,duetolackofunderstandingofprefabricationtechnology,somestakeholdersdecidetoadopt prefabricated IDC after the main civil structure has been finished. In such cases,matchingtheinteriorspaceandthepre-definedmodulesismorechallenging.Additionalwork,such as cutting the existing modules to fit into the dimensions, has to be conducted onsite,leadingtoconsiderable material wastage.Interviewee2reflectedthat:

If prefabricated bathrooms are adopted, then the level, slope, waterproof, and space forthedrainagesystemshould beintegrated,requiringdepth forslopingofat least300 mm.

Withoutearlyengagementofinteriordesigner, manufacturer,andcontractor,prefabricatedIDCproject delivery is hugely problematic. For instance, some clients adopt hollow bricks for wallconstruction to save costs. These walls are unsuitable for a prefabricated interior because theycannot provide enough support for the bolts that need to be embedded to install wallboards.Moreover,somestakeholdersreducefloor-to-floorheighttomaximizesaleablearea,but

prefabricatedinteriorprojectsrequireadditionalceilingspace.Interviewee5suggestedthat:
If we could have an early engagement, we would suggest leaving some holes or space forlocatingequipmentatthesamelevelastheflorbeamsorslabswithoutsacrificingstoreyheight.

Modulardesign
Modular design is unanimously a DfMA enabler for prefabricated IDC. Usually, the interiordesignerkeepssomeofthemostcommonlyadoptedmodulesofdifferentsystemsinmind. Forexample, the case study firm has a long-term cooperation with some suppliers, who provide alist of modules that they can produce efficiently and economically in advance. The interiordesigners will then select modules from that list. Usually, types of prefabricated IDC modulesareratherlimiteddueto equipmentandtechnologyconstraints.Forprefabricatedconstruction,typesofmodulesaremuchmorediversifiedandcustomizedgiventheirdevelopmentoverfivedecadesandrelativelymatureequipmentandtechnology(MarchesiandMatt,2017).Interviewee8 said that:
There may be only three most commonly used types of modules for the floor system, e.g.,300 mm×300 mm, 400 mm×400mm and 500 mm×500mm. The interior design will selectoneof thethreeto matchthe room's dimension and minimizematerial wastage.

Therearesomeexceptionsformoduleselection. Sometimes,theexistingmodulescannotmatchthedimensionsofaroom.Iftheprojectisonalargescale,interiordesignerswillnegotiatewithmanufacturers tosee whether theycancustomize particular modulesforthe project.However,itisnoteasyformanufacturers toproducecustomizedmodules.Interviewee12 explainedthat:*The manufacturer has to make new moulds and adjust the equipment to produce customizedmodules,whichisextremelycostly. Assuch,onlyiftheprojectislargeenoughinscale will themanufacturer agreetoproducecustomized modules.*

Connectiondetaildesign
Connectiondetaildesignisacriticalfactoraffectingthequalityandperformanceofprefabricated projects. As prefabricated IDC is still in its infancy, great efforts have beendevoted to exploring connection detail design, for example, through cross-sectoral learning.Interviewee10 reflectedthat:
Due to the lack of relevant experience, our company has employed some experts from theautomotive industry to see whether the connection detail design from a relatively matureindustrycan beappliedto offsiteIDC.

Thecasestudy firmhasdevelopedvarioustechnologiesforconnectiondetaildesigninprefabricated IDC project systems (see Figure 2). The floor system consists of three layers:levelling stents, GRC (glass fibre reinforced concrete) basal plate, and surface plate, e.g.,ceramictileorwoodparquet.Usually,oneGRCbasalplateissupportedbyfourlevellingstents

at the bottom and covered by one surface plate at the top. This three-layer structure in the floorsystem applies interlocking connection design between elements. Onsite workers just need tolevelthefourstentstokeepthem inthesameplanehorizontallyandconnectdifferentelementsmanually,withouttheneedtouselargeamountsofemulsionvarnish.Forthewallsystem,threetypesofconnectiondetaildesignhavebeendeveloped:skirtinglineconnection,stitchconnection,andtightconnectioninresponsetoblock-brickbasedwall,hollow-brickbasedwall,and shear wall, respectively. The wallboard is connected with a light gauge steel joist by aphysical connector. The connection detail design of the integrated ceiling system is the mostcomplicated. Interviewee5 said that:

We adopted a kind of end cap in 'L' shape to connect the elements of the gypsum boardintegrated ceiling system. However, some customers feel it affects the aesthetics as theconnectionwouldleadtoaninevitablegapbetweenelements.Therefore,wehavedevelopedanew connection to overcomethis drawback.

Figure2.Connectiondetaildesign andconstructionoffloor,wall,andceilingsystems

Designsimplification

Designsimplificationinvolvesvarioustechniques.First,thedesignphilosophyatthecasestudyfirm is to pursue simple and flat design, which means the elements will be kept in very basicgeometry, and some unique geometries are forbidden (see Figure 3). For example, the use ofarch elements is minimized as manufacturers still have difficulty designing the connectiondetails and producing this structure. Design simplification contributes to the simplification ofproduction,logistics,andassemblyprocess.Thisdesigntechniquealsoreflectstheobjectiveofoffsiteconstruction to achievemass production(Monizzaet al., 2018).

Figure3. Designusingbasic geometryin real-life projects

The simplification of connection detail types and designs is also critical for improving theefficiencyofonsiteassembly,asfewerconnectiontypes meanlessdependenceontheskillsofonsite workers. The case study firm aspires to the simplicity of IKEA furniture and LEGOassembly, such that non-professionals could quickly assemble their products. Interviewee 14explained that:

Initially, we have eight types of connection, three for the wall system, two for the floorsystem, two for the integrated bathroom system and one for the integrated ceiling system.Now, we have unified the types of connection design for the wall and integrated ceilingsysteminto one.

Design should also support interior component integration and offsite production processes.Designers have endeavoured to shift most of the workload from onsite to offsite to achieve theobjectivethatallelementsareindependentproduct.Accessories,e.g.,intelligentswitches,

should be integrated offsite, so their onsite assembly by workers does not demand too muchexpertise.Onecompellingexampleofconstructiontechnologysimplificationbythecasestudyfirmis in wallpaperingwork.Interviewee5explainedthat:

Traditionally,weneedatleastsevenstepstoconductthewallpaperingwork.Now,wejustneed two steps onsite, installing the light gauge steel joist and attaching the surface platewith a physical connector. Most work can be conducted offsite, e.g., attaching a PVC(PolyvinylChloride)membraneon its surface.

It is also recommended to reduce the number of elements to a minimum, a form of DfMAthinking that has been seen in Tesla (Synnes and Welo, 2016). For example, for spaces 1.20 min length, modules 600 mm in length is preferred over 300 mm as then the manufacturer onlyneeds to produce two modules, and onsite workers will need to assemble the two modules at atime.Interviewee10 saidthat:

If we find a 200 mm gap when using the module of 600 mm, we would consider whether asinglemoduleof 800 mmcould beadopted instead of dividing into two modules.

Finally,aconsistentmodules' numbering processthroughout design,manufacturing,andassembly has been well established in the case study firm. It facilitates the manufacturer andonsite workers to quickly comprehend and execute the design, minimizing human error ormisunderstandingandsimplifyingtheworkingprocedure.Interviewee11explainedthat:

Wewillenvisiontheconstructionsequenceoftheonsiteworkers.Duringthisprocess, from design to construction, we would consecutively number the modules. Afterwards, themanufacturerwillproducethesemodulesinthesameorder.Finally,theonsiteworkerswillalso assemblethesemodules accordingly.

Designstandardization

Design standardization is a crucial DfMA enabler for prefabricated IDC. Presently, residentialunit designs vary from one to another depending on project conditions, laws and regulations,and users' requirements. This variation is not convenient for interior prefabrication and designstandardization. To encourage interior DfMA and offsite IDC, the concept of house typestandardization should be embedded throughout a broader range of stakeholders. For example,if a house is 93 m^2 or 120 m^2, its layout and dimensions should be standardized even acrossdevelopers.Interviewee10said that:

Now,weareworkingtowardsthisobjectivebycollaboratingwithsomeleadingstakeholdersin China,such as EvergrandeandVanke, tostandardizethe housetypes.

The dimensions of elements made of different materials should also be standardized andcoordinated across manufacturers. For example, many standard material dimensions, e.g.,calcium silicate plate or bamboo woodfibreboard, are 200 mm or its multiple in length. Theothermanufacturersshould alsoproduceelementswith lengths of 200mm,400 mm, 600 mm,

and so on. By establishing such a standard, manufacturers could keep modules inventorywithoutconsideringthemarketmuch, furtherfacilitatingmanufacturingandassembly efficiency.Interviewee4added that:
WearenowcollaboratingwithChinaBuildingDecorationAssociationtoestablishsuchastandard.

Thecasestudyfirmhasalsostandardizedtheprocurementprocess.Forexample,theprocurementprocessfortheelementsinthefloorsystem,wall systemandintegratedbathroomsystemhaveall beenstandardized.Theprocessisapplicabletoalmostallprefabricatedinteriorprojects and allows both manufacturers and onsite workers to quickly comprehend the interiordesign. Apparently, the achievement of such a standardization technique requires coordinationfromall stakeholders in theIDC supplychain.

Elementshape,weight,anddimensionconcerns
Whendesigningtheshape,weight,anddimensionsofaprefabricatedinteriorelement,variouslimitationsshouldbeconsidered,includingtransportationmethod,vehicle,liftandstairs,roomentrance,andeaseofhandlingandassembly.Forexample,dimensionsshouldnotexceedthoseof vehicles, lift, or stairs (see Figure 4). In main structure construction, tower crane are used todeliverheavymaterials,butinteriorconstructionmaterialsareusuallydeliveredviaservicelift, thuslimitingthedimensionsofelementssignificantly.Sometimestheliftisunavailable,sotheelements have to be handled manually and manoeuvrable, without damage, around cornersbetween flights of stairs. The dimensions of integrated sanitary ware, consisting of threeelements(chassis,wall, andtop)are aparticular challenge.Interviewee15explained that:
The chassis is usually in a size of 2 m×2 m, but many times the construction of the mainstructurehasbeenfinishedwhenweconductheinterior,andtheentranceofthebathroomis just 2 m×1.2 m. Given that, we need to consider dividing the whole element into twopiecesand assemblethem onsite.

Figure4.Component shape,weight,and dimensionconcerns

Regarding element weight, handling equipment should be considered during interior design. Ifa handling bracket is used, how many elements should be bundled into one package withoutoverloading should be calculated. The same applies if the elements are to be carried manually,toavoidoverburdeningonsiteworkers.Interviewee9 provided the examplethat:
In terms of the calcium silicate integrated plate, three such plates should be bundled sothatthe total weight, e.g.,50kg,is suitable to betaken bytwo onsiteworkers.

Material-lighteneddesign
Material-lightened design enables prefabricated elements to be manufactured and assembledefficientlyandsafely.Thecasestudyfirmhasdevelopedanewtypeoflightweightconcrete

for use in their projects, reducing weight by one third. It also always coordinates with itsmanufacturers to condense elements to as small a depth as possible without jeopardizingmaterial performance and durability. This strategy benefits all stakeholders as the thinner theelements,thelarger spaceavailableforotherpurposes.Interviewee8 addedthat:

Basedonour exploration,wearenowabletousesomeelements in anextremedepth.Forexample, we use a ceramic plate with a depth of 6 mm (see Figure 5) or a calcium silicateplatewith a depth of 5 mm.

Figure5.Ceramicplate witha depthof 6mmin real-lifeprojects

However, adopting a material-lightened design strategy can be difficult. Use of an alternativelightweightmaterialorcondensingt oanextremedepthmustalsobealliedtootherfact ors.Forexample,intheintegratedceilingsystem ,fireresistanceratematters,whilewaterandcorr osionresistance are the key for the wall system. In the floor system, a 500 mm×500 mm basal plate,shouldbear loadingof atleast 2 tons.

Interviewee13addedthat:

Even if the material properties can fulfil all the requirements, the cost is another decisivefactor.

Technology-rationalizeddesign

Therationaladoptionofsomedigitaltechnologi estoaidtheoffsiteIDCprocessisanimportantDf MA enabler. Presently, BIM technologies have been widely applied to many prefabricatedprojects.Thecasestudyfirmadopt stwoBIMroutesintheirinteriordesign.First,itu sesRevit,aBIMsoftwaredevelopedbyAutodes k,tofacilitatecoordinationasitsuseisuniversala mongAECindustrystakeholders.Usingthemo delsbuiltbyRevit,thefirmcansimulatethepracti calconstruction process to detect any errors, such as overlapping pipelines, and correct them.Afterwards, it extracts a detailed working plan from Revit and sends it to the project managerforprecise installationonsite.

However, it is time-consuming and costly to train professionals in the use of Revit, furtherexacerbated by the fact that existing software is not easily adaptable to prefabricated IDC.Hence, the case study firm has developed its own BIM software for prefabricated IDC, called‘FunPlus’(seeFigure6).Thefirminputsal lthemodulesindifferentdimensionsandmateria ls,connection types, construction technologies and even price. During the BIM process,thedesignersjustneedtoselecttheprope rmodulesandconstructiontechnologies, withouthavingtoadjust some parametersastheydo in Revit.Interviewee17explained that:

Afterwards, we can quickly extract the Bill of Quantities (BOQ) of all the materials andsend it to the manufacturers for immediate procurement.This practice canenhanceworkingefficiency.

Figure6.BIMprocesswith ‘FunPlus’inareal-lifeprojects

Knowledgeandinformationmanagement

As the development of prefabricated interiors is still in its early stage, proper knowledge andinformation sharing and management are essential for successful project delivery. In practice,veryfewpractitionershaveagoodunderstandingofconstructiontechnologies.Inevery project,the case study firm has a three-level technology training process, including technical trainingof the project manager by the decoration technology designer, onsite worker group leaders bytheprojectmanager andonsiteworkersbytheir groupleaders.Interviewee 13added that:

Our designers will visit the sites regularly to gain the workers' opinions on whether thedesign and current technologies are convenient and straightforward enough and what wecandointheinteriordesignprocessforfurtherimprovement.Thisisakindofbidirectionalknowledgeand information sharing process.

Thecasestudyfirmalsoregularlyarrangesdemonstrationmeetingsforknowledgeandinformation sharing among interior designers, technology designers, BIM designers, projectmanagers,andotherprofessionals.Interiordesignissometimesmorefocusedonaesthetics,buttheexecutionoftheirdesignreliesmoreontechnologydesigners.Insuchmeetings,stakeholderslearnfromeachotherabouta wide rangeofcriteriafrom differentperspectives.

Materialsselectionandcombination

The selection and combination of materials for offsite IDC projects is even stricter than intraditional projects. Environmental friendliness and geographical difference are two criticalmaterialselectioncriteria.Intermsofenvironmentalfriendliness,fortraditionalIDC,a3-to6-month transitional period is typically required to let some harmful gases, e.g., formaldehydeand benzene, fully emit from materials before the occupancy stage. Environmentally friendlymaterials and a dry installation process for prefabricated IDC shorten this transitional period,anduserscanmoveinimmediately.This poseshigherrequirementstothematerials.Interviewee8 said that:

We only ever spent 12 days completing the prefabricated IDC for a residential unit withan areaof 97 m^2.

The case study requiresthatall materialsusedina prefabricated interior fulfilE0-classenvironmental standards, which stipulate a formaldehyde content of no more than 0.5 mg/L,the highest standard internationally. Moreover, to increase the reuse and recycling rate, allmodules are detachable and decomposable. Wide adoption of virgin materials, such as timberand stone, in traditional IDC has caused severe ecological damage, so virgin materials are notsuggestedin theprefabricatedinterior projects.Interviewee5 said that:

We try to select some artificial composite materials, e.g., rigid vinyl plank (see Figure 7),a new developed composite material to replace the traditional wood floor. We also use animitationmarble plate toreplacethe original marble for the wall.

Figure7.Someartificialcompositematerialsinreal-lifeprojects

Regarding geographical difference, the selected material properties should align with thetemperature,humidity,andcorrosivityofthegeographicallocationinwhichtheyaretobeused.For example, bamboo wood fibreboard is not recommended for use in extremely cold places,as it will become brittle and cracked, but is preferred in places with very high humidity, as ithasagoodwaterabsorptionabilities.Incoastalregions,eithergalvanizedorplasticscrewscanbe a wise choice for better corrosion resistance. Before using a new material, its geographicalfeasibilityandcompatibilityto prefabricationmustthereforebetested.

Discussion

The arrival of offsite IDC brings both opportunities and challenges to the AEC industry. Ittransforms traditional artistic interior design, and site-intensive and time-consuming in-situconstruction, making it more manageable and systematic through the adoption of innovativeoffsite construction technology (Friedmann& Savage, 2020; Jaillon& Poon, 2008). ThisempiricalinvestigationrevealsthatoffsiteIDCreliesonawell-integratedsupply chain,standardized production procedures in a factory-like environment, advanced planning andschedulingofbuildingcomponentslogistics,dryinstallationprocesses,andadvancedmachinery involvement. These characteristics challenge conventional professional practice,architecturalandinteriordesignmethods,stakeholders'rolesandresponsibilities,andorganizational structure. Also, since prefinished interior components must be considered fromthebeginningtoimproveoffsiteconstructability,offsiteIDCchangesthepositionoftheinteriordesign team from follower of architectural and engineering design (Havenhand, 2004) tocollaboratorin thecollaborativedesignprocess from thebeginning.

To facilitate this process, DfMA encourages the interior design methods of, for example, earlycoordination for a well-prepared construction, design simplification and standardization forfacilitating the production process, exploring design opportunities without neglecting criteriafrom the transportation stage, and selecting standard components from a supply chain insteadof crafting or customizing for a specific area. These can be regarded as assistive tools or time-saving standards for practitioners to prepare an interior design scheme and deliver the bestpractice. Although many interior DfMA enablers, at first glance, are similar to those proposedinthepreviousliterature(Tanetal.,2020),theirdetails,interpretations,andutilizationsarenotidentical.Rather,theymainlyfocusontheinternalormicroscaleenvironment,includingspacearrangement and functions, surface materials, interior modules and elements, and dimensions,toeaseoffsiteproduction,component and moduletransportation,and assemblyflows.

ComparingDfMAenablersforoffsiteIDCwith conventionalpractice,itbecomesapparentthatitsrealizationwillconfrontvariouschallenges.First,asoffsiteIDCneedsearlierdecision-

makingfromupstreamdesign,involvedstakeholdersmustovercomethechronicfragmentationin the AEC industry. Second, successful implementation of DfMA and offsite IDC relies notonly on designers but integration of the whole supply chain, including proprietors, developers,and manufacturers. For instance, integrated and standardized interior modules can be achievedonly if many manufacturers in the supply chain are coordinatedto produce standardizedmaterials, and then only if designers include these materials in a design. Finally, there exists astereotypical perception that the products of offsite technology lack aesthetic value, are toostandardizedtosatisfy customizeddemands,andare inferior inquality due tolightenedmaterials (Steinhardt & Manley, 2016). To counter this, IDC stakeholders should devote moreefforts to developing offsite IDC and improving end-users' confidence. Overall, a healthyecosysteminvolvingvariousstakeholdersintheIDCsupplychainmustbeestablishedtounlockthepromiseof offsiteIDC and DfMA.

This study has limitations in four areas. Firstly, the reliability and replicability of a single casestudyareinevitablyaconcern(Yin,2009;Flyvbjerg,2006;Yangetal.,2021;Zhaoetal.,2020),although we selected one of the largest IDC companies in China as a case study, and it indeedprovided many insights. Secondly, as offsite IDC emerged only recently, even a sizeablecompanyliketheonestudiedherehasacquireditsinsightsmainlyfromresidentialprojects.TowhatextenttheDfMAenablerscanbeappliedtoothertypesofoffsiteIDCprojectsisunclear. Thirdly, this study is mainly qualitative in nature. A subjective intention of the authors may beimposedoninterpretationofthedatacollected,leadingtopossiblebiasintheinterpretedresults, despitemeasurestaken(e.g.,groupdiscussions, multi-roundrevisions)tominimizeit.Fourthly,the results are mainly based on the interpretations of the 18 interviewees. Due to difficulties ofaccessibilityandliaison,resultsarenotvalidatedthroughfocus groupdiscussionorinterviewswith IDC practitioners and scholars outside the case study firm. This likely affects the validityand generalizabilityof theresults in a widercontext.

Conclusion

OffsiteIDCisaninnovationintheAECindustrythatcanrevitalizesite-intensiveconventionalconstruction by the establishment of a supply chain, the machinery involved in the production,well-planned transportation, and standardized dry assembly method. From the initiation stageofabuilding'slifecycle,DfMAhasgreatpotentialtoassistinthedesignofinteriorcomponentsandinfacilitatingtheiroffsiteproductionandassembly.Thisstudyidentifies10DfMAenablersfor offsite IDC: (1) collaborative design, (2) modular design, (3) connection detail design, (4)simplification,(5)standardization,(6)material-lighteneddesign,(7)shape,weightanddimensionsofelements,(8)knowledgeandinformationmanagement,(9)technology-rationalized design, and(10) material selection and combination. Interior designers mustcollaboratefromthestart,integratewiththesupplychain,consideroffsiteconstructionprocesses,andselectandcomposestandardcomponentsandmaterials.Thesefindingshighlightthechangesinbothinteriordesignmethodologyandconstructionstakeholders'rolesand

responsibilities.Theyalsoexpandunderstandingofof DfMAandoffsitetechnologyfromarchitecture to interior inthe AEC industry.

The advantages of offsite IDC suggest it will increase in popularity while the use of DfMA forthis purpose will gradually extend to various building types. However, full benefits of thisinnovativedesignandconstructionmethod willonlybeenjoyedbytheAECindustrywhenthesupply chain is well established and coordinated and the market is prosperous enough. Thus,more developers, designers, manufacturers, couriers, contractors, and vendors are encouragedto coordinate and step into this value chain. The 10 DfMA enablers for offsite IDC identifiedhere are just some examples. Future research is recommended to explore the innovativeness ofoffsiteIDCandinteriorDfMAenablersinothersettingsandbuildingtypes,suchashealthcareand hospital facilities and from other construction stakeholders' perspectives. The trend ofintegrating home appliances and automation with interior components in offsite IDC shouldalsobeinvestigated.

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