Use of BIM and Prefabrication to Reduce Construction Waste

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Abstract

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It is estimated that the US generated on average 12 million tons construction waste per year between 1996 and 2014. The literature showed that prefabrication can use the material more efficiently, thus reduce the waste. And Building Information Modeling is necessary to provide the precise building product dimension and location information for prefabrication. Interview results showed that operational savings are more than material savings. Five case studies were evaluated, one showed that with use of prefabrication, BIM and careful construction sequence planning, on-site waste generation rate is between 15% to 45% lower than EPA study result of an average of 4.34 lb/ft^2. However, the other four case studies seemed to be much higher than EPA's average rate, suggesting a need for more sampling.

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DEDICATION

To my loving family.

1. Introduction

From a few pieces of pipes laying outside mechanical room to the dumpsters for general waste and wood, these are the wastes we see on construction sites. The passage of Paris Accord by 194 countries showed how much people care about the environment now. [1] Construction waste is also an environmental issue. USEPA estimated that there were 10.98 million tons of construction wastes generated in the US in 1996, and 15.1 million tons in 2003. [2] A statistic published by Seattle Public Utilities shows that construction and demolition waste accounts for 31% of all waste stream in Seattle. [3] Literature review showed that Building Information Modeling (BIM) and prefabrication projects generated less waste; the review also looked at how BIM evolved from spatial relationship between human figure and building elements, how prefabrication can be traced to the 19th century and how BIM model's precise dimension enables prefabrication. This thesis is to study the link between BIM enabled prefabrication projects and waste reduction quantitatively; and methods used in selecting component for prefabrication. If the link is found to be strong, it can serve as an encouragement to use BIM enabled prefabrication more, to reduce construction waste and harness associated schedule and cost benefits.

2. Literature Review

2.1 Waste

Construction Waste Estimation

USEPA gathered data from 95 residential projects and 12 commercial projects and found the average waste generation rate was 4.39 lb/ft² for residential projects, and 4.34 lb/ft² for commercial projects. Based on $353,652 million residential construction value and $256,501 million commercial construction value reported by Department of Commerce for 2003, and average construction cost of $76.80 per ft² for the residential project and $111 per ft² for the commercial project, reported from Census data, EPA estimated that 15.1 million tons of construction wastes were generated in 2003 (10.1 million tons residential, 5 million tons commercial, not including demolition) [2] and 10.98 million tons were generated in 1996 (6.56 million tons residential, 4.42 million tons commercial, not including demolition). [4]

Table 1 Estimated Amount of Building-Related C&D Materials Generated in the U.S. During 2003

	Residential		Nonresidential		Totals	
Source	Million tons	Percent	Million tons	Percent	Million tons	Percent
Construction	10	15%	5	5%	15	9%
Renovation	38	57%	33	32%	71	42%
Demolition	19	28%	65	63%	84	49%
Totals	67	100%	103	100%	170	100%
Percent	39%		61%		100%	

The approach EPA used was to take Census data of construction cost, divided that number by a proprietary cost per square foot, i.e. Dodge Data of McGraw-Hill total residential spending and square footage, to get the overall construction square footage. Then multiply it by the averaged waste generation rate from sample projects.

The formula is described below, and same formula is also used for nonresidential construction. [2]

$$\left(\begin{array}{c}\text{Total U.S. Residential}\\ \text{Construction Waste (tons/year)}\end{array}\right) = \frac{\left(\begin{array}{c}\text{Total Residential Construction}\\ \text{Put in Place Value (\$/year)}\end{array}\right)}{\left(\begin{array}{c}\text{Average Cost Per Area of}\\ \text{Residential Construction (\$/ft)}\end{array}\right)} \times \frac{\left(\begin{array}{c}\text{Average Waste Generated Per Area}\\ \text{for Residential Construction (lb/ft)}\end{array}\right)}{2000\ lb/ton}$$

The report also has a table describing how it was calcualted.

Table A-1
Residential Construction Debris Worksheet

Method to Use

(1) Start with total dollars of new construction, from Census Bureau. Current Constr Reports, C-30.
(2) Calculate sq ft of new construction from total dollars and $/sq ft construction cost.
(3) From empirical waste assessment, estimate lb/sq ft of new construction.
(4) Calculate total generation.

Calculation

(1) C-30, Residential Construction (1996) = $181,795,000,000
(Includes private new housing units and public housing & redevelopment)

(2) 1995 Census data, Table 1175 of 1996 Stat Abs. (Note: whole industry not included)

Residential Construction	$127,900,000,000
Residential sq ft of new constr	2,172,000,000 sq ft
Cost of new construction	$58.89 per sq ft

Total sq ft of new constr = 181,795,000,000/58.89/1.03 2,997,326,036 sq ft
(Includes 3 percent inflation factor)

(3) See sampling waste assessment results:

Average Generation = 4.38 lb/sq ft

(4) Total new residential construction debris = 6,564,000 tons/year

Figure 1 Table showing residential construction waste calculation [2]

In order to understand how line (1) was calculated, a research on 1997 U.S. Census Abstract Table 1180 was done.

No. 1180. Value of New Construction Put in Place: 1990 to 1995

[**In millions of dollars.** Represents value of construction put in place during year; differs from building permit and construction contract data in timing and coverage. Includes installed cost of normal building service equipment and selected types of industrial production equipment (largely site fabricated). Excludes cost of shipbuilding, land, and most types of machinery and equipment. For methodology, see Appendix III]

TYPE OF CONSTRUCTION	CURRENT DOLLARS					CONSTANT (1992) DOLLARS				
	1990	1993	1994	1995	1996, prel.[1]	1990	1993	1994	1995	1996, prel.[1]
Total new construction	**468,532**	**482,737**	**527,063**	**547,079**	**568,908**	**479,016**	**464,985**	**487,644**	**486,666**	**496,299**
Private construction	**361,054**	**362,587**	**400,008**	**410,196**	**427,776**	**370,102**	**347,754**	**367,898**	**363,086**	**372,453**
Residential buildings	182,856	210,455	238,874	236,597	246,899	188,045	200,502	217,996	207,392	213,619
New housing units	127,987	144,071	167,919	162,898	176,378	131,632	137,243	153,250	142,790	152,606
1 unit	108,737	133,282	153,838	145,009	156,510	111,832	126,960	140,416	127,108	135,411
2 or more units	19,250	10,788	14,081	17,889	19,868	19,800	10,283	12,833	15,682	17,196
Improvements	54,869	66,384	70,955	73,699	(NA)	56,414	63,259	64,746	64,601	(NA)
Nonresidential buildings	143,506	110,635	120,285	133,949	140,692	146,661	106,729	111,416	119,835	123,361
Industrial	33,636	26,482	28,947	32,301	30,068	34,373	25,554	26,803	28,902	26,372
Office	35,055	20,920	22,178	25,254	25,191	35,838	20,197	20,553	22,603	22,083
Hotels, motels	10,679	4,565	4,648	7,201	11,147	10,917	4,405	4,308	6,438	9,775
Other commercial	40,047	32,453	37,551	42,272	44,966	40,922	31,292	34,756	37,809	39,423
Religious	3,566	3,887	3,869	4,318	4,490	3,642	3,748	3,584	3,862	3,936
Educational	4,616	4,649	4,822	5,493	6,211	4,715	4,484	4,471	4,915	5,442
Hospital and institutional	10,868	12,492	12,268	11,173	11,346	11,103	12,050	11,377	9,998	9,949
Miscellaneous [2]	5,040	5,188	6,002	5,937	7,273	5,151	5,000	5,565	5,309	6,379
Farm nonresidential	2,801	3,291	3,246	3,473	(NA)	2,862	3,174	3,007	3,107	(NA)
Public utilities	28,933	34,925	34,713	33,348	(NA)	29,537	34,120	32,717	30,169	(NA)
Telecommunications	9,803	9,619	10,157	10,747	11,162	9,891	9,468	9,875	9,798	9,781
Other public utilities	19,130	25,306	24,556	22,601	(NA)	19,646	24,652	22,842	20,372	(NA)
Railroads	2,600	3,108	3,340	3,341	(NA)	2,633	3,056	3,186	3,046	(NA)
Electric light and power	11,299	15,567	14,918	13,126	(NA)	11,572	15,096	13,877	11,825	(NA)
Gas	4,820	5,645	5,300	5,205	(NA)	5,013	5,536	4,861	4,667	(NA)
Petroleum pipelines	411	986	998	929	(NA)	428	965	918	834	(NA)
All other private [3]	2,957	3,281	2,890	2,829	2,458	2,997	3,229	2,763	2,583	2,170
Public construction	**107,478**	**120,150**	**127,055**	**136,883**	**141,132**	**108,914**	**117,231**	**119,747**	**123,579**	**123,846**
Buildings	43,615	52,071	53,930	59,783	63,418	44,583	50,167	49,882	53,373	55,541
Housing and redevelopment	3,808	4,855	5,247	6,156	5,417	3,914	4,629	4,788	5,397	4,688
Industrial	1,434	1,718	1,465	1,510	1,414	1,465	1,658	1,358	1,351	1,241
Educational	16,055	22,103	23,457	25,608	28,185	16,398	21,314	21,731	22,905	24,709
Hospital	2,860	3,666	3,940	4,345	4,674	2,924	3,537	3,652	3,888	4,100
Other [4]	19,458	19,730	19,821	22,164	23,729	19,882	19,029	18,353	19,832	20,803
Highways and streets	32,105	34,341	37,671	38,159	39,406	31,777	34,205	36,463	34,931	34,480
Military facilities	2,665	2,453	2,318	3,002	2,878	2,683	2,405	2,196	2,721	2,529
Conservation and development	4,686	5,909	6,370	6,389	5,753	4,870	5,745	6,002	5,798	5,109
Sewer systems	10,276	9,354	10,081	10,869	11,256	10,670	9,095	9,499	9,859	9,993
Water supply facilities	4,909	5,373	5,388	6,085	6,421	4,987	5,143	4,911	5,407	5,602
Miscellaneous public [5]	9,223	10,649	11,298	12,597	12,000	9,344	10,470	10,793	11,491	10,592

NA Not available. [1] Includes estimates for types of construction indicated as (NA). [2] Includes amusement and recreational buildings, bus and airline terminals, animal hospitals and shelters, etc. [3] Includes privately owned streets and bridges, parking areas, sewer and water facilities, parks and playgrounds, golf courses, airfields, etc. [4] Includes federal administrative buildings, prisons, police and fire stations, courthouses, civic centers, passenger terminals, space facilities, postal facilities, etc. [5] Includes open amusement and recreational facilities, power generating facilities, transit systems, airfields, open parking facilities, etc.

Source: U.S. Bureau of the Census, *Current Construction Reports*, series C30, *Value of New Construction*, monthly.

Figure 2 Total Residential/Nonresidential Construction Put in Place Value [5]

It shows line (1) was a sum of New housing units in Private sector and Housing and redevelopment in Public sector, as summarized in the table below.

Table 2 Total Residential Construction Put in Place Value

	1996
Private construction	
New housing units	176,378
Public construction	
Housing and redevelopment	5,417
Total Residential	181,795
Source	No. 1180 (1997)

Line (2) was from U.S. Census Abstract 1996 Table 1175 from Dodge Data.

No. 1175. Construction Contracts—Value of Construction and Floor Space of Buildings, by Class of Construction: 1980 to 1995

[Includes new structures and additions, and major alterations to existing structures which affect only valuation, since no additional floor area is created by "alteration". See also, *Historical Statistics, Colonial Times to 1970*, series N 78-100]

YEAR	Total	Residential buildings	NONRESIDENTIAL BUILDINGS									Nonbuilding construction
			Total	Commercial [1]	Manufacturing	Educational [2]	Hospital	Public buildings	Religious	Social and recreational	Miscellaneous	
VALUE (bil. dol.)												
1980	151.8	60.4	56.9	27.7	9.2	7.4	5.4	1.6	1.2	2.7	1.7	34.5
1981	157.3	56.3	65.5	35.2	9.3	6.6	6.4	1.4	1.2	3.4	2.0	35.4
1982	157.1	55.0	64.6	32.3	9.6	6.8	8.0	1.9	1.2	2.8	2.0	37.5
1983	194.1	88.4	67.9	38.3	5.4	7.1	8.5	2.1	1.5	2.9	2.1	37.8
1984	214.3	95.3	82.1	48.2	7.9	8.5	7.4	2.7	1.7	3.3	2.4	36.9
1985	235.6	102.1	92.1	54.6	8.1	10.0	7.8	3.1	2.0	4.0	2.5	41.4
1986	249.3	115.6	91.6	52.4	7.3	11.7	7.9	3.2	2.1	4.2	2.8	42.1
1987	259.0	114.1	98.8	53.7	8.6	13.2	9.0	4.7	2.1	4.3	3.2	46.1
1988	262.2	116.2	97.9	51.6	9.5	14.1	8.2	4.4	2.2	4.7	3.2	48.1
1989	271.3	116.2	106.1	53.6	12.7	15.9	8.8	5.2	2.0	5.0	2.9	49.0
1990	246.0	100.9	95.4	44.8	8.4	16.6	9.2	5.7	2.2	5.3	3.1	49.7
1991	230.8	94.4	86.2	32.7	8.3	19.0	9.6	6.2	2.4	5.1	3.0	50.2
1992	252.2	110.6	87.0	32.8	8.9	17.6	10.9	5.8	2.5	5.5	3.1	54.6
1993	271.5	123.9	88.8	34.2	9.0	19.3	10.5	3.9	2.4	6.8	2.6	58.9
1994	296.2	133.6	101.0	40.9	10.7	21.0	10.5	6.1	2.5	6.5	3.0	61.6
1995	303.8	127.9	112.4	46.5	12.4	22.9	10.7	6.1	2.9	7.1	3.8	63.5
FLOOR SPACE (mil. sq. ft.)												
1980	3,102	1,839	1,263	738	220	103	55	18	28	49	52	(X)
1981	2,805	1,562	1,243	787	188	83	60	14	25	46	41	(X)
1982	2,455	1,440	1,015	631	119	82	71	19	25	38	30	(X)
1983	3,387	2,276	1,111	716	112	84	84	20	29	36	31	(X)
1984	3,661	2,311	1,350	901	157	100	70	23	29	37	34	(X)
1985	3,853	2,324	1,529	1,039	165	111	73	28	32	44	38	(X)
1986	3,935	2,481	1,454	960	148	129	73	30	32	44	39	(X)
1987	3,756	2,288	1,469	933	160	139	78	42	32	46	38	(X)
1988	3,594	2,181	1,413	883	162	142	71	38	32	49	37	(X)
1989	3,516	2,115	1,400	867	158	151	72	41	27	48	35	(X)
1990	3,020	1,817	1,203	694	128	152	69	47	29	51	32	(X)
1991	2,634	1,653	981	476	100	177	72	50	29	45	33	(X)
1992	2,799	1,864	936	462	95	156	77	41	30	42	32	(X)
1993	3,062	2,091	971	481	110	165	75	30	30	51	29	(X)
1994	3,410	2,266	1,144	601	142	172	72	45	30	51	31	(X)
1995	3,448	2,172	1,276	700	160	185	69	39	33	56	33	(X)

X Not applicable. [1] Includes nonindustrial warehouses. [2] Includes science.

Figure 3 Table used to calculate Average Cost per Area of Residential/Nonresidential Construction [5]

Nonresidential was calculated in the same matter, as shown in the table below.

Table A-2
Nonresidential Construction Debris Worksheet

Method to Use

(1) Start with total dollars of new construction, from Census Bureau. Current Constr Reports, C-30.
(2) Calculate sq ft of new construction from total dollars and $/sq ft construction cost.
(3) From empirical waste assessment, estimate lb/sq ft of new construction.
(4) Calculate total generation.

Calculation

(1)	C-30, Nonresidential Construction (1996)	$198,694,000,000	
	(Includes all private nonres and public industrial, educ, hosp & other)		
(2)	1995 Census data, Table 1175 of 1996 Stat Abs. (Note: whole industry not included)		
	Nonresidential Construction	$112,000,000,000	
	Nonresidential sq ft of new construction	1,276,000,000	Sq ft
	Cost of new construction	$87.77	per sq ft
	Total sq ft of new construction = 198,694,000,000/87.77/1.03		
	(Includes 3 percent inflation factor)	2,197,759,570	sq ft
(3)	See sampling waste assessment results:		
	Generation =	4.02	lb/sq ft
(4)	Total new residential construction debris =	4,417,000	tons/year

Figure 4 Table showing nonresidential construction waste claculation [2]

Line (1) was a sum of Nonresidential buildings from Private sector and Industrial, Educational, Hospital and Other from Public sector, as summarized in the table below.

Table 3 Total Nonresidential Construction Put in Place Value

	1996
Private construction	
Nonresidential buildings	140,692
Public construction	
Industrial	1,414
Educational	28,185
Hospital	4,674
Other	23,729
Total Nonresidential	198,694
Source	No. 1180 (1997)

Once the method EPA used is known, the construction waste of other years can be calculated by looking up Census data, and summarized below.

Table 4 Estimated Construction Waste for New Constructions 1996-2002

	1996	1997	1998	1999	2000	2001	2002
Private construction							
New housing units	179,448	187,328	213,909	249,536	264,864	279,772	298,450
Public construction							
Housing and redevelopment	4,614	3,795	4,047	5,618	5,228	4,751	5,507
Total Residential	184,062	191,123	217,956	255,154	270,092	284,523	303,957
Private construction							
Nonresidential buildings	150,350	167,610	181,915	195,776	210,140	201,094	167,084
Public construction							
Industrial	1,389	999	1,012	925	1,159	1,556	1,906
Educational	24,112	28,915	29,916	39,725	43,500	55,752	56,154
Hospital	4,638	4,934	3,978	3,968	4,007	4,053	4,932
Other	23,907	24,846	27,183	27,454	28,321	30,855	33,572
Total Nonresidential	204,396	227,304	244,004	267,848	287,127	293,310	263,648
Source	No. 1194 (1998)	No. 1195 (1999)	No. 1195 (1999)	No. 1191 (2000)	No. 930 (2001)	No. 914 (2002)	No. 936 (2003)

Note that in 2003, Bureau of Census has changed the classification and provided the mapping table. The Bureau published the Value of New Constructions table in both old and new classification, allowed an opportunity to match the two. An attempt was made to work with the new classification by summing up the categories, the difference in as shown in the following table.

Table 5 Reclassification Mapping Check

	Private	Public	Total
Old Classification			
Residential	279,391	5,096	284,487
Nonresidential	202,334	89,311	291,645
New Classification			
Residential	279,391	4,568	283,959
Nonresidential	201,111	86,567	287,678

With that effort, estimation for 2003 to 2014 was made based on published census data. [5]

Table 6 Estimated Construction Waste for New Constructions 2003-2014

	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
Private												
New single family	310,575	377,557	433,510	415,997	303,447	186,111	106,288	112,726	108,178	132,015	168,823	193,600
New multi-family	35,318	38,495	48,228	53,020	49,149	44,105	29,264	14,022	15,037	22,231	32,151	41,806
State and Local Government												
Residential	5,281	5,191	6,749	4,340	5,073	4,908	6,048	7,407	5,962	4,683	4,476	4,136
Total Residential	351,174	421,243	488,487	473,357	357,669	235,124	141,600	134,155	129,177	158,929	205,450	239,542
Private												
Lodging	9,946	11,542	12,809	17,687	28,604	36,237	25,033	11,014	8,395	10,783	13,872	15,698
Office	30,413	33,112	36,823	46,194	55,195	57,455	40,286	24,408	23,738	27,963	30,746	38,403
Commercial	57,680	61,582	69,143	72,148	81,745	81,891	53,654	37,998	39,723	43,163	46,770	60,761
Farm (subtract)	5,284	5,123	7,232	5,277	5,812	7,330	6,132	7,346	6,561	6,951	6,932	9,835
Health care	23,648	26,706	27,723	33,183	36,780	37,883	36,760	30,758	28,906	30,767	29,751	28,556
Educational	13,384	12,722	12,787	13,745	16,572	18,806	16,619	13,599	14,081	16,440	16,588	16,699
Religious	8,481	8,080	7,772	7,690	7,464	7,074	6,287	5,260	4,205	3,739	3,429	3,242
Public safety	191	289	380	448	500	681	463	234	205	121	131	219
Amusement and recreation	7,892	8,553	7,693	9,041	9,350	10,948	7,718	6,288	6,744	5,788	6,189	7,481
Manufacturing	14,231	23,517	30,914	34,278	37,599	63,189	74,135	38,105	38,869	45,833	48,679	57,239
State and Local Government												
Office	8,258	8,616	7,365	5,478	6,174	9,548	9,227	8,025	7,440	5,989	5,140	5,379
Commercial	3,058	2,888	2,734	1,580	1,614	1,742	2,293	1,555	1,682	1,399	1,166	870
Health care	5,228	6,531	8,019	5,514	6,996	7,157	7,110	6,077	7,009	7,021	6,932	6,249

Educational	59,286	57,923	64,666	70,931	80,030	83,608	83,846	71,101	67,965	65,740	60,469	61,033
Public safety	7,753	7,746	8,544	6,618	8,621	9,501	9,408	7,594	7,245	7,428	6,435	6,224
Amusement and recreation	11,262	10,878	10,452	8,943	10,819	11,494	10,553	9,826	8,542	8,776	8,066	8,799
Air Passenger terminal	3,883	4,558	3,550	3,728	5,151	6,154	6,180	7,059	5,681	5,005	5,597	4,876
Land Passenger terminal	2,255	1,569	1,008	3,152	1,191	1,633	2,381	3,758	3,223	2,887	3,215	3,746
Water Dry dock/marine terminal	252	323	427	362	553	402	270	603	414	463	525	469
Total Nonresidential	261,817	282,012	305,577	335,443	389,146	438,073	386,091	275,916	267,506	282,354	286,768	316,108
Source	No. 923, No. 924 (2004-2005)	No. 925, No. 926 (2006)	No. 930, No. 931 (2007)	No. 929, No. 930 (2008)	No. 922, No. 923 (2009)	No. 929, No. 930 (2010)	No. 959, No. 960 (2011)	No. 964, No. 965 (2012)	No. 982, No. 983 (2015)	No. 982, No. 983 (2015)	No. 982, No. 983 (2015)	No. 985, No. 986 (2016)

Table 7 Estimated Construction Waste for New Constructions 1996 - 2014

Year	C-30, Residential Constr (million dollars)	Residential Constr (million dollars)	Residential sq ft of new constr (million)	Cost of new constr (dollar/ft2)	Total sq ft of new constr (million)	Total estimated amount of residential constr materials generated (million tons)	C-30, Non-residential Constr (million dollars)	Non-residential Constr (million dollars)	Non-residential sq ft of new constr (million)	Cost of new constr (dollar/ft2)	Total sq ft of new constr (million)	Total estimated amount of non-residential constr materials (million tons)	Total Waste (million tons)	
1996	184,062	146,300	2,476	59.09	3,115	6.84	204,396	120,000	1,293	92.81	2,202	4.78	11.62	No. 1194, No. 1195 (1998)
1997	191,123	152,600	2,566	59.47	3,214	7.05	227,304	136,500	1,510	90.40	2,514	5.46	12.51	No. 1195, No. 1196 (1999)
1998	217,956	173,000	2,902	59.61	3,656	8.03	244,004	134,000	1,581	84.76	2,879	6.25	14.27	No. 1195, No. 1196 (1999)
1999	255,154	195,000	3,253	59.94	4,256	9.34	267,848	168,700	1,838	91.78	2,918	6.33	15.68	No. 1191 (2000), No. 913 (2010)
2000	270,092	208,300	3,113	66.91	4,036	8.86	287,187	173,300	1,869	92.72	3,097	6.72	15.58	No. 930 (2001), No. 913 (2010)
2001	284,523	219,700	3,159	69.55	4,091	8.98	293,310	169,100	1,669	101.32	2,895	6.28	15.26	No. 914 (2002), No. 913 (2010)
2002	303,957	248,700	3,356	74.11	4,102	9.00	263,648	155,100	1,436	108.01	2,441	5.30	14.30	No. 936 (2003), No. 913 (2010)
2003	351,174	283,400	3,689	76.82	4,571	10.03	261,817	156,100	1,404	111.18	2,355	5.11	15.14	No. 923, No. 924 (2004-2005), No. 913 (2010)
2004	421,243	333,100	4,061	82.02	5,136	11.27	282,012	164,400	1,457	112.83	2,499	5.42	16.70	No. 925, No. 926 (2006), No. 913 (2010)
2005	488,487	384,000	4,346	88.36	5,529	12.14	305,577	182,400	1,527	119.45	2,558	5.55	17.69	No. 930, No. 931 (2007), No. 913 (2010)
2006	473,357	342,100	3,648	93.78	5,048	11.08	335,443	217,200	1,637	132.68	2,528	5.49	16.57	No. 929, No. 930 (2008), No. 913 (2010)
2007	357,669	263,100	2,656	99.06	3,611	7.93	389,146	238,500	1,669	142.90	2,723	5.91	13.83	No. 922, No. 923 (2009), No. 913 (2010)

2008	235,124	162,200	1,583	102.46	2,295	5.04	438,073	243,600	1,379	176.65	2,480	5.38	10.42	No. 929, No. 930 (2010), No. 913 (2010)
2009	141,600	111,800	1,107	100.99	1,402	3.08	386,091	165,700	763	217.17	1,778	3.86	6.94	No. 959, No. 960, No. 961 (2011)
2010	134,155	119,700	1,146	104.45	1,284	2.82	275,916	155,000	645	240.31	1,148	2.49	5.31	No. 964, No. 965, No. 966 (2012)
2011	129,177	127,000	1,159	109.58	1,179	2.59	267,506	165,900	704	235.65	1,135	2.46	5.05	No. 982, No. 983, No. 984 (2015)
2012	158,929	166,300	1,479	112.44	1,413	3.10	282,354	159,200	779	204.36	1,382	3.00	6.10	No. 982, No. 983, No. 984 (2015)
2013	205,450	209,700	1,832	114.47	1,795	3.94	286,768	176,400	868	203.23	1,411	3.06	7.00	No. 982, No. 983, No. 984 (2015)
2014	239,542	231,400	1,929	119.96	1,997	4.38	316,108	218,900	984	222.46	1,421	3.08	7.47	No. 985, No. 986, No. 987 (2016)

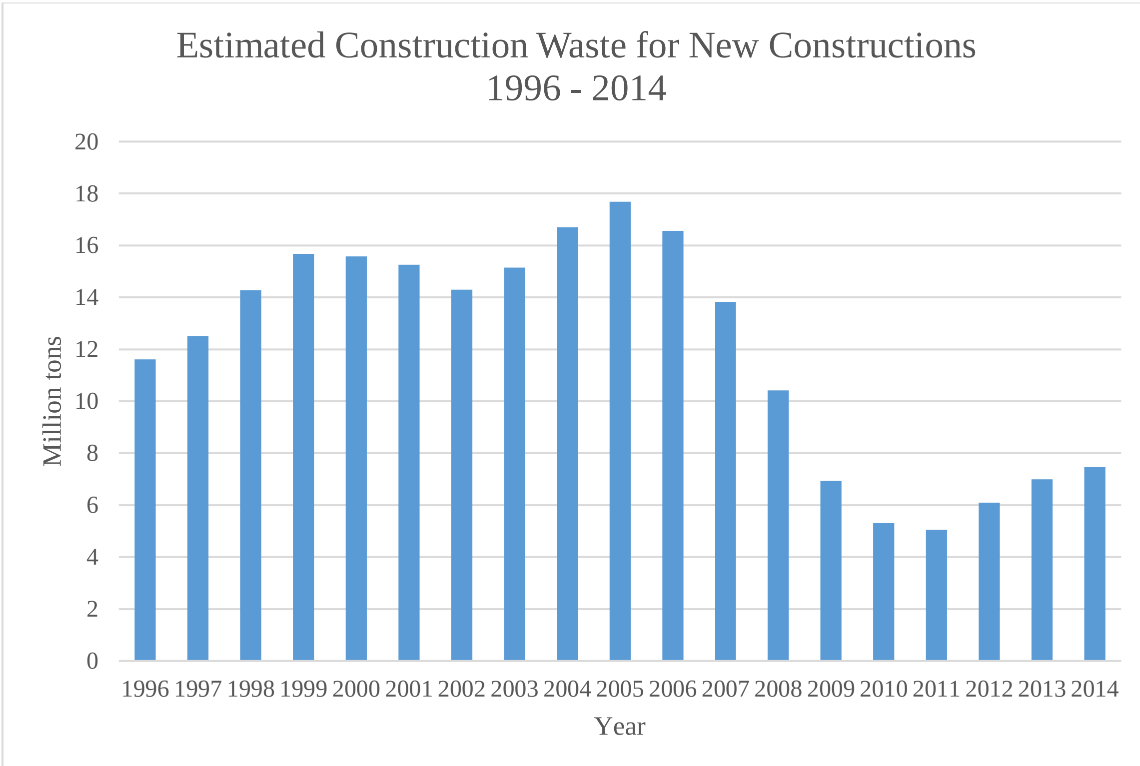


Figure 5 Estimated Construction Waste for New Constructions 1996 - 2014

Northeast Waste Management Officials' Association (NEWMOA) published a report on construction and demolition waste. The data was gathered from waste facilities from seven of its member states. [6] The results showed the contents of the waste, its volume, and the percentage.

Table 8 NEWMOA Estimated C&D Waste for Seven Member States [6]

Material	Estimated Quantity Generated in the Northeast (tons)	Percentage by Weight (%)
Plastics	240,793	2
Metals	601,982	5
Concrete and Rubble (ABC)	1,083,569	9
Drywall		
- Construction (clean)	722,379	6
- Demolition/Renovation (dirty)	481,586	4
Roofing	1,324,361	11
Wood:		
- Unadulterated (construction scraps and pallets)	1,384,559	11.5
- Adulterated (painted and engineered)	2,516,286	20.9
- Treated (pressure-treated)	192,634	1.6
Other	3,491,497	29

Waste Sources and Commonly Suggested Solutions

Gavilan & Bernold developed a framework on waste sources. [7] Faniran & Caban adapted the list and conducted a survey to 10 Australian contractors. [8] The survey asked the respondents to rate the sources as 'very significant', 'significant', 'of minor significance', or 'not significant'. The percentage of respondents rating the cause as 'very significant', they called 'severity index', ranked the causes of the wastes. Faniran & Caban also suggested some solution for the wastes. Waste & Resources Action Programme (WRAP) also developed a framework of causes and solutions.[9] On reducing off-cuts, Faniran & Caban and WRAP all suggested design to stock material dimensions to reduce off-cut wastes. Liu suggested using a BIM model to check architectural elements, e.g. wall surface area, against stock material dimension to estimate wastage, and use it as support information for design iteration to design-out the wastage. [10]

Table 9 Faniran & Caban Framework [8]

Description	Severity Index (%)
Design changes	52.4
Leftover material scraps	42.9
Non-consumables	38.1
Design/detailing errors	28.6
Poor weather	23.8
Inadequate materials control plan	14.3
Inadequate materials handling	14.3
Materials storage	9.5
Procurement errors	9.5
Site accidents	9.5
Poor workmanship	4.8
Criminal damage/theft	0

Table 10 Faniran and Caban Suggested Solutions [8]

1. Timely communication of design changes.
2. Dimensioning to avoid cutting-to-fit.
3. Clear specification of project goals by the owner to avoid flawed design decisions.
4. Attention to detail to avoid design and planning errors.
5. Contractor to detect design errors.
6. Planning of construction process and material storage to reduce waste caused by poor weather.

RS Means estimating handbook suggests adding wastage allowance to quantity take-off. [11] Since the estimating handbook is largely based on data collected from real life projects, it can be seen as the actual extent of material wastage; thus, the possible amount that can be saved, besides the wastage from design changes and design errors.

Table 11 RSMeans Suggested Wastage Allowance [11]

Material	Allowance (%)
Division 3	
- Ready-Mixed Concrete	5
- Concrete Reinforcing lapping, splicing, waste	10
- Concrete Reinforcing welded wire fabric	10
Division 5	
- Brick and CMU	3
- Mortar	25
Division 6	
- Lumber	5 - 10 depending on material quality and complexity of the framing
Division 9	
- Lath	5
- Acoustic Treatment	5

2.2 Prefabrication

Eliminate the material waste at the source

Detail fabrication process is easier to be achieved in a shop environment or through automation; [12] it can be more efficient and create less waste. Aladdin, a modular house brand, used to arrange wood cut so more parts can be made from a piece of wood in 1917. [13] With the same idea, CNC plasma machine can be used to cut as many parts as it can be arranged out of one sheet of tin today. Taylor from Health and Safety Executive of the UK government conducted a study on prefabrication and noticed that companies using CNC machines for cutting, aligning, fastening, and painting drastically reduced material waste; the waste generated was also controlled and recycled. [14]

Levels of Prefabrication

The building can be categorized into the primary element for the load bearing structure, and secondary elements for building envelope, internal fit-out and technical services. [13, 15, 16] Most of the time, this is also how prefabricated component are categorized. For example, precast concrete and steel column and beam are structure units, curtain walls belong to the envelope, and MEP racks belong to the service systems.

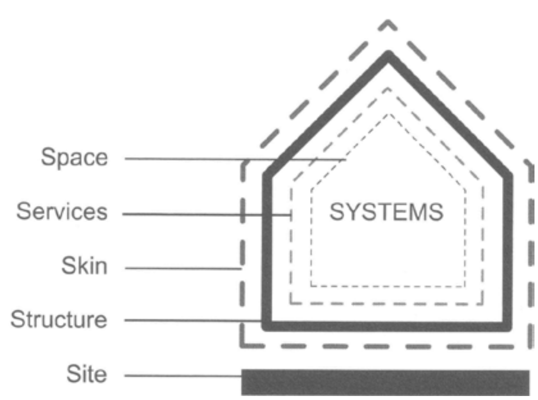


Figure 6 Building element categories [13]

The level of prefabrication can be distinguished into three categories: components, panels and modules. [13, 15, 16] At the component level, vinyl frame window is a good example of a prefabricated component. At the panel level, curtain wall, and prefabricated roof truss, partition wall, and patient room headwall are panelized systems. [13] Stacked up room module and prefabricated bathroom pod belong to the module level.

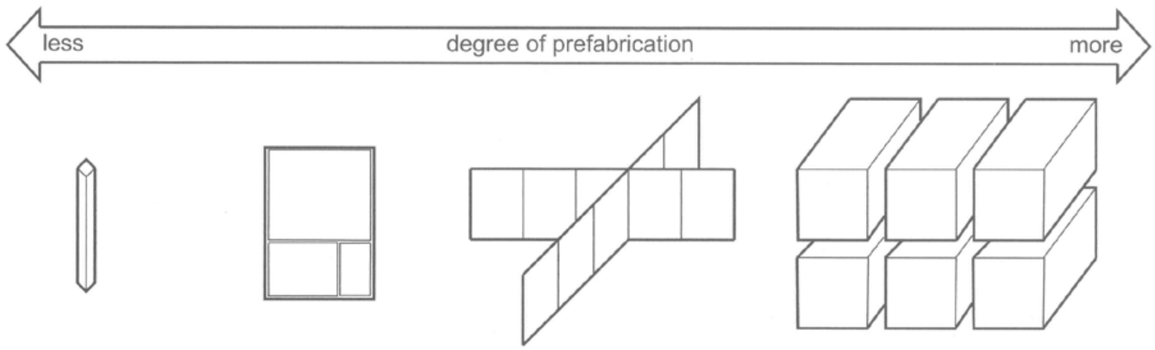


Figure 7 Degree of prefabrication [13]

Common Selection Methods

Complexity is a common method for selecting prefabrication component, MEP racks and patient room headwalls are good examples. [17] Repetition is another common way of selecting prefabricated units, for example, bathroom pods. [17] Another method that is less common, but can also be effective, is actively looking for processes that have the potential to eliminate waste, ordering stud to length, as an example, can eliminate cuttings on-site and scrap pieces, also increase installation speed. [18]

Figure 8 MEP racks [17]

Figure 9 Bathroom pods [17]

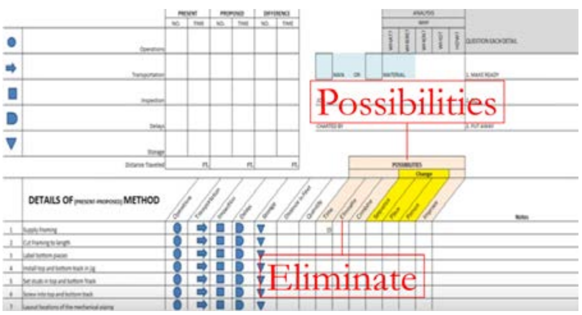


Figure 10 Process flow chart [18]

Figure 11 Ordered to length metal studs [18]

Published Prefabrication Case Studies

Warrior Transition Barracks is a 120-units barracks building in Fort Carson, Colorado. Mortenson was the general contractor for this design-built project. Prefabrication features used in this building were prefabricated bathroom pods and prefabricated metal roof truss modules. The result was 35% waste reduction compared to similar projects, along with two and half months, or 14% schedule savings. [19]

Miami Valley Hospital Heart & Orthopedic Center in Dayton, Ohio is a 480,000 ft² structure that is designed by NBBJ and built by Skanska. Nearly 35% of the building components were prefabricated, including bathroom pods, patient room headwall, footwall, casework, and MEP racks; the studs were also ordered to length. It resulted in 60% waste reduction and two months schedule savings. [20]

CAD, CAM, CNC and BIM for Prefabrication

R. Smith described that information and communication revolution has flattened the design to delivery of the buildings. At the moment, Computer-Aided-Design (CAD) is used to design the building, Computer-Aided-Manufacturing (CAM) is used to design components and Computer Numerical Controlled (CNC) machines fabricate components that were designed in CAM; but there is a trend of automation by integrating CAD, CAM software and CNC machines. [13]

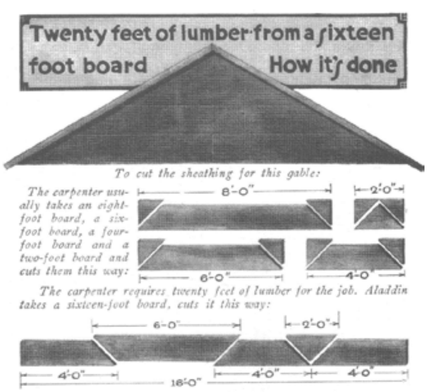


Figure 12 Aladdin's method of cutting wood [13]

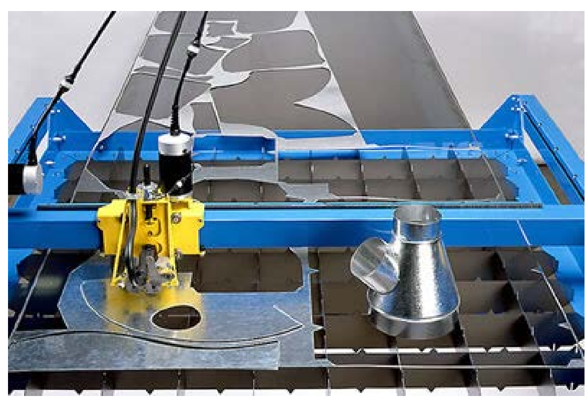


Figure 13 CNC plasma sheetmetal cutter [21]

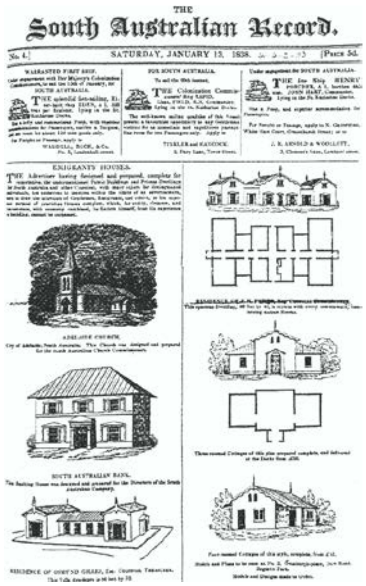
NIST formed a team to Japan to study their construction technologies in 1995. The team noticed a steel fabricator NKK (now JFE Holdings) has an integrated bridge design and fabrication system. It took NKK three years to develop the design software, with additional three years for the fabrication system. The 3-D based design software is capable of producing inspection drawings, structural coordinate drawings, member piece drawings, manufacturing drawings, member lists and assembly drawings. The fabrication system produces data for numerically controlled tools for cutting, welding and assembly; it is also capable of finding optimal path for laser cutting. [22]

Venables et al. were sponsored by the UK Department of Trade and Industry to visit German offsite manufacturers, to see progress in this field. They found that Glatthaar Fertigkeller, the largest prefabricated basement producer in the country, who supplies to about 40 modular house manufacturers, has in their most advanced factories, computer controlled equipment, that can take panel dimensions, and the size and location of openings, right from the digital files from their customers. [23]

A $44 million, 110,000 ft^2 healthcare expansion project in North Carolina was built by Rogers Builders. The BIM model for the project was utilized to facilitate structural steel and MEP systems shop drawings. [24]

History of Prefabrication

Prefabrication is not a new idea, prefabricated wood frames that are similar to the framing used for the houses we live in today can be traced to the early 19th century. An example shown below is prefabricated houses available to Australian that were manufactured in England and shipped to Sydney. [15] Cast iron was used for fabricating column and joists on Benyon, Bage & Marshall flax mill in Shrewsbury in 1797, and prefabricated external wall on James Bogardus owned company headquarters in New York in 1848. Bogardus and Daniel Badger both sold prefabricated external cast iron walls that were available on catalogs at the time. Precast concrete was used to build a casino by François Coignet in Biarritz in 1891. [15] From the 19th century to today, there were numerous prefabrication and architectural movements; [13] besides the balloon frames, another successful one was Ludwig Mies van der Rohe's design of Seagram Building in New York in 1958 that defined the modern-day skyscrapers. [13]


THE

South Australian Record.

No. 4.] SATURDAY, JANUARY 13, 1838. [Price 5d.

WARRANTED FIRST SHIP.

FOR SOUTH AUSTRALIA.

EMIGRANTS' HOUSES.

ADELAIDE CHURCH.

SOUTH AUSTRALIAN BANK.

Figure 14 Prefabricated houses on Australian newspaper in 1838 [15]

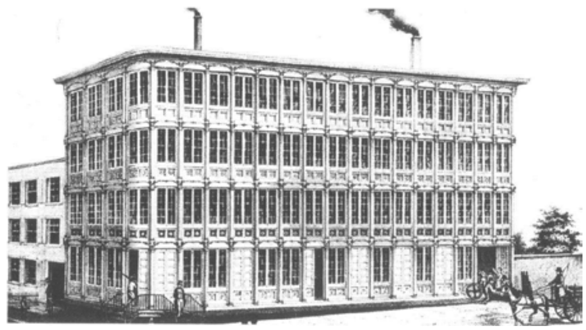


Figure 15 Bogardus Company [15]

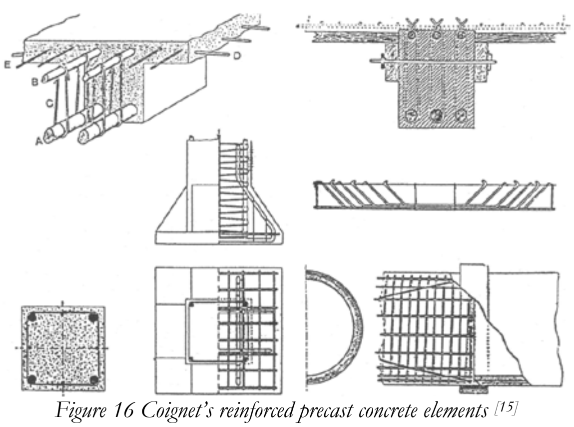


Figure 16 Coignet's reinforced precast concrete elements [15]

Figure 17 Seagram Building [25]

2.3 Building Information Modeling

Provides Precise Dimension and Location for Prefabrication

When we look at construction drawing, we see the gridlines, which were transferred from architectural drawings; architects use the grid to give them a sense of order without consciously thinking of it. [16] The gridline was developed from spatial relationship of human figure and building elements, as illustrated in Le Corbusier's figure drawing. These information then is translated into measuring units such as inches and feet, [16] then digitalized into coordinates.

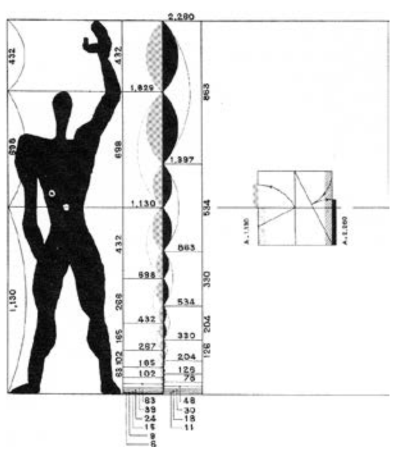


Figure 18 Le Corbusier figure drawing [16]

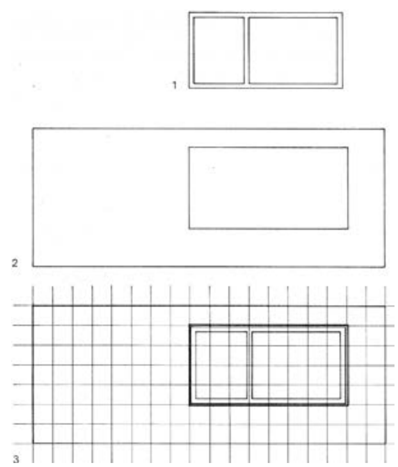


Figure 19 Elements and gridlines [16]

Once the spatial information is digitalized, it can be used in the design process. Traditionally, consultants provide schematic design to ensure the project's functionality, but not the constructability; then the specialty contractors produce the shop drawings and do the coordination for constructability. [24] Where BIM comes in is that it provides the precise dimension and location of the components needed for prefabrication. Heger explained that he sees the x, y, z coordinate as a unique identifier for an element; it provides information about where things are, so when the architects and clients give their design decisions along the construction process, they put that into the BIM model; the model's precision allows the components to be prefabricated if wanted, making it ready to go into the construction site. [18]

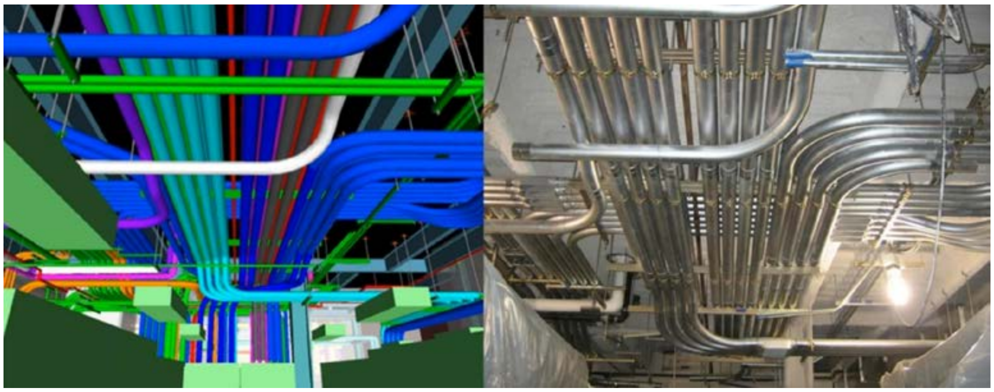


Figure 20 Coordinated BIM model and actual construction [17]

BIM for Coordination and Front-Load Design

Another quality of BIM is that the files are transferred electronically, i.e. they are uploaded to and download from a File Transfer Protocol (FTP) server, the design team can agree to update the models at a time interval, e.g. weekly, so all disciplines can have each other's latest design. For minor design changes, the coordination can be done in as little as one day, so the contractor gets the latest Site Instruction with updated drawings on-site. This achieves "quickly and effetely communicate design changes" suggested by Faniran & Caban, in reducing the waste.

BIM alone cannot reduce the waste, however. It is also the completeness of design. For example, site work can start when the building permit is received, but the building permit can be applied with Design Development drawings. The incomplete design could lead to changes and the possibility of rework and waste. This concept is similar to RS Means' 10% contingencies for Design Development drawings and 3% for Final Working Drawings, WRAP's "use design freeze to avoid change" and

Boyd's idea that design work at the early stage has a higher level of influence to the project cost. [9, 11, 26]

Table 12 RSMeans Suggested Contingencies [11]

Drawing Stage	Contingencies (%)
Conceptual	20
Schematic	15
Preliminary working drawing (design development)	10
Final working drawing	3

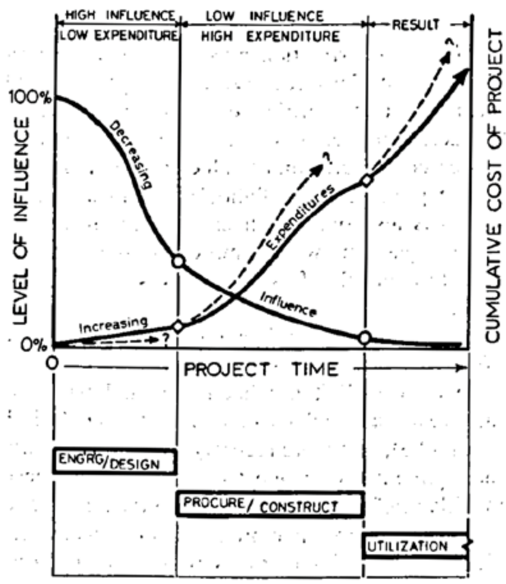


Figure 21 Level of Influence on Project Costs [26]

Published Prefabrication and BIM Construction Waste and Operational Savings

A survey to 809 architects, engineers and contractors by Bernstein et al., showed that prefabrication not only reduced the waste but also decreased project schedule and budget. [27] Two South Korean projects, a twin residential towers and a baseball training facility, have BIM models made after design; Won et al. compared the coordinated BIM model and the original design and found that BIM coordination solved design errors, thus saved potential rework. [28] Jones et al. also noticed the BIM-prefabrication relationship and called it 'BIM driven prefabrication'; they conducted a survey to 305 architects, engineers (civil and structural only) and contractors; 31 % of them reported 25% or more on-site labor reduction due to offsite fabrication, and 27% reported 25% or more on-site labor productivity increase due to the model-based process. [29] As mentioned in International Organization for Standardization (ISO) Environmental Management Systems, a well-executed environmental practice may also result in financial and operational benefits. In the case of reducing the waste through BIM and prefabrication, schedule and cost savings may also be harnessed. [30]

Table 13 Bernstein et al. Prefabrication Reduces Construction Wastes [27]

Wastes Reduction	Participants (%)
More than 15%	13
6% - 15%	31
1%-5%	32
No change	22
Increased	2

Table 14 Bernstein et al. Prefabrication Decreases Schedule [27]

Schedule Decrease	Participants (%)
4 weeks or more	35
3 weeks	10
2 weeks	14
1 week	7
No change	28
Increased	6

Table 15 Bernstein et al. Prefabrication Decreases Project Budget [27]

Budget Decrease	Participants (%)
More than 20%	5
11% - 20%	17
6% - 10%	19
1% - 5%	24
No change	27
Increased	8

Table 16 Won et al. Estimated BIM Saved Rework [28]

Project type	Floor area (m^2)	Actual waste (m^3)	Estimated saved rework (m^3)	Savings (%)
Two residential towers	120,000	6,495	1168.3	15.2%
Baseball training facility	9,995	1,957	87.3	4.3%

Table 17 Jones et al. High Impact BIM benefits [29]

Description (>25%)	Participants (%)
Reduced on-site labor due to offsite operation	31
Increased on-site labor productivity	27

BIM and Prefabrication as Trending Technologies

A survey done for World Economic Forum shows that BIM and prefabrication were top two technologies participants believed will have the greatest impact and are likely to be realized. [31] The National Research Council was asked by the National Institute of Standards and Technology (NIST) to form an ad hoc committee to give advice on increasing competitiveness and productivity of the U.S. construction industry. The committee conducted a two days workshop with more than 50 experts. Among the five recommendations that they gave, one was widespread deployment of BIM; another was greater use of prefabrication. [32]

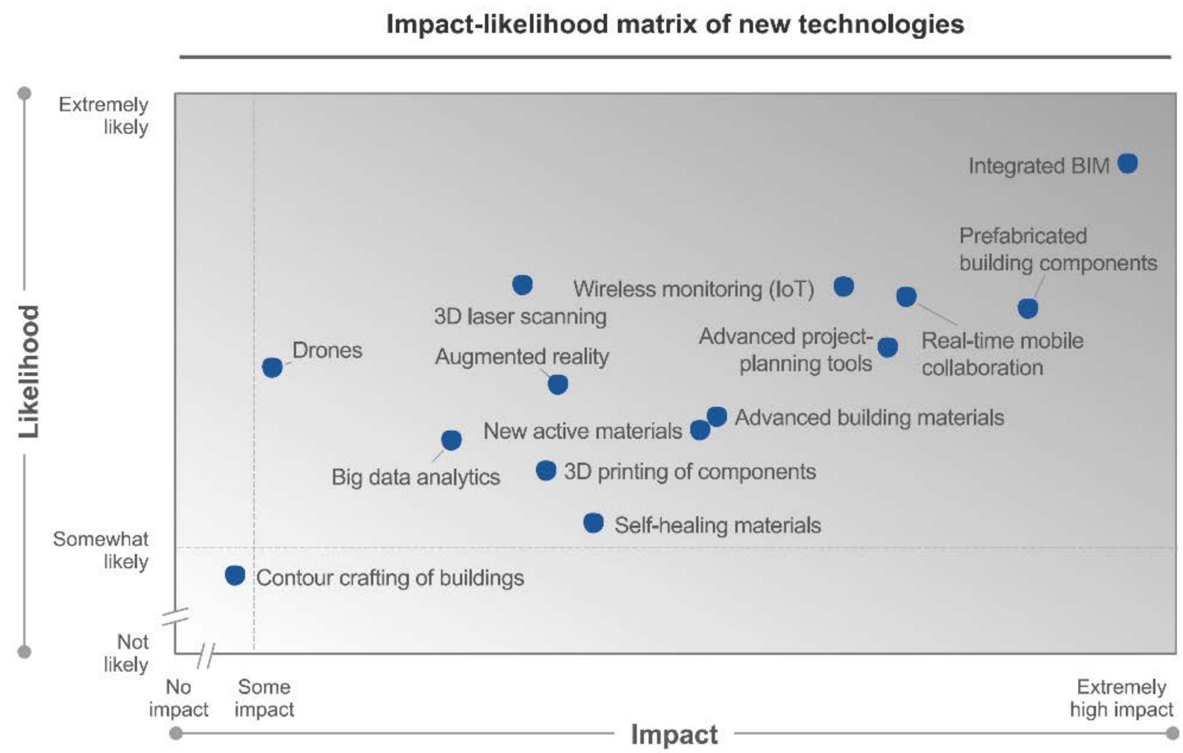


Figure 22 Impact-Likelihood Matrix of New Technologies [31]

3. Methodology

A data collection sheet for construction waste that went to landfill was adapted and modified from examples found in ISO 14044 Life Cycle Assessment. [33] It will be used to study the amount of waste from projects or processes. The unit on the form can be volume, weight, cost or other measurements, but not a proportionated value that is not based on an empirical number. [33] If the results contain weight and project area, it then can be used to compare to the EPA's 4.39 lb/ft^2 residential, 4.34 lb/ft^2 commercial value, as this is the only known baseline number. As per the rational that BIM and prefabrication projects are better coordinated, Won et al.'s study and Bernstein et al.'s survey, the expected result is that BIM and prefabrication projects generated less waste.

The prefabrication selection recording sheet is modeled after the Landfill data sheet. Its purpose is to study the various ways prefabrication components were selected, to expand the knowledge of choosing methods, to allow more components qualified for prefabrication within a project, thus increase waste savings, associated cost and time benefits. [30] The expected result could be selection based on complexity, repetition, waste elimination, as per Smith & Juan, and Heger, [17, 18] the result may also yield other new criteria.

4. Interviews

The original purpose of the interviews was to learn from experienced people how they selected construction methods. The literature review showed prefabrication can reduce construction waste and BIM can provide the precise dimensions and locational information required for prefabrication. The literature review also showed common methods used for selecting components for prefabrication, i.e. repetition, complexity, etc. Therefore, it was thought that gathering the application-side-of-things would help people practicing prefabrication. However, it was quickly realized during the first interview, that experienced people do not see things like the common methods; they focus more on detail planning. Thus, the revised purpose was to learn people's experience in using prefabrication and BIM to reduce construction waste.

Four people were interviewed for the study. All of them now work as owner's representatives. One is an architect, and two started as superintendents before becoming project managers. They have between 10 to 30 years of industry experience. Three of them have worked for large national contractors prior to coming to the owner's side. The first person was selected because his publication was identified during the literature review. The other three people were selected by referrals because of their interest in green buildings.

The questions for the first person were geared toward the original purpose on selection methods and the construction waste study that he had done.

1. How did you become interested in lean?
2. When you look at a new project, what steps do you take to identify possible items for prefabrication and how do you decide what to prefab? Once you picked the components for

prefabrication, do you go through another internal discussion, and how do people usually agree on what to prefab?

3. You developed a checklist, what information are included in the checklist? How do you use it?
4. You have conducted a study on reducing waste on a job. What kind of project was it? How did you measure the weight of incoming materials, recycled and landfill waste?
5. You also mentioned 10 – 15% extra materials that's not getting built, was that for this particular project, which means other projects will be more, or was the 10 - 15 the percentage for typical projects?
6. What did you do to achieve the high waste saving rate?
7. You mentioned prefabricate to the largest module possible, do you still think it's a good overall approach?
8. Any other thoughts?

The questions for other people were focused on the revised purpose of learning of their experience with using prefabrication and BIM to save waste. Without knowing their projects histories, open-end questions were chosen, so they could discuss their personal experience as much as possible.

1. What kind of projects have you done?
2. Is there an example that used BIM and prefabrication?
3. How do you think the BIM model can be used to reduce the waste, in the sense as process that people can put into use?
4. How do you think the prefabrication can be used to reduce the waste?
5. Is there something you think that worth to try/improve?

4.1 Waste

The term waste stream describes how waste flows like a stream. It is an accumulation of different sources, to the downstream in this case, the construction site. A building is like a living organism. Its structure as bones, its envelope as skin, and then waste as waste. If the dumpster is full, the workers next cannot do their job (it can shut down the project). So the constructors must begin to control the waste. Once good at controlling the waste, they must focus on controlling the source (of the waste).

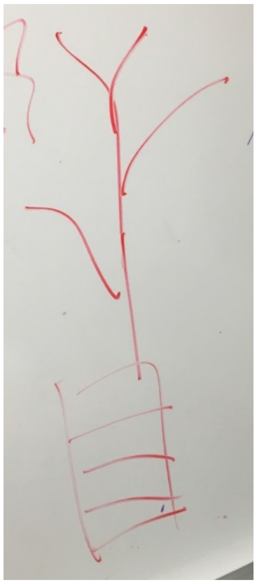


Figure 23 Waste stream

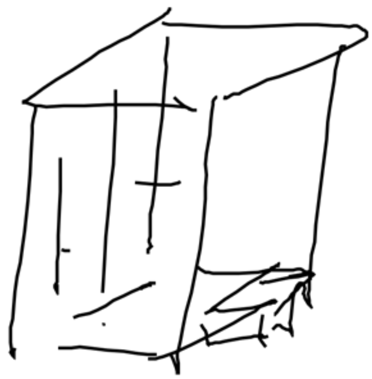


Figure 24 Building as a living organism

Everything that gets thrown out is money. It takes money to buy them in the first place.

We cannot eliminate the waste. We can improve the efficiency of the waste, e.g. prefab, recycle in the factory vs. cumulated on-site then send to cumulated recycler. A more complete picture may be comparing Constructed On-site Unit vs Packaging Pellet + Prefabricated Unit.

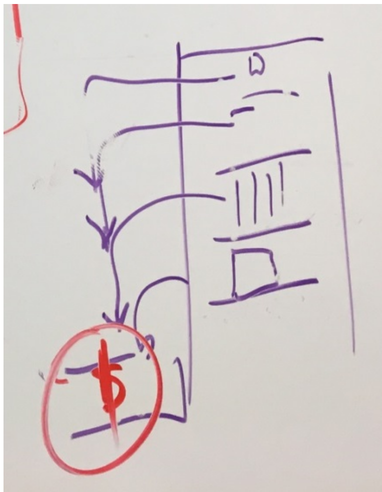


Figure 25 Everything got thrown out is money

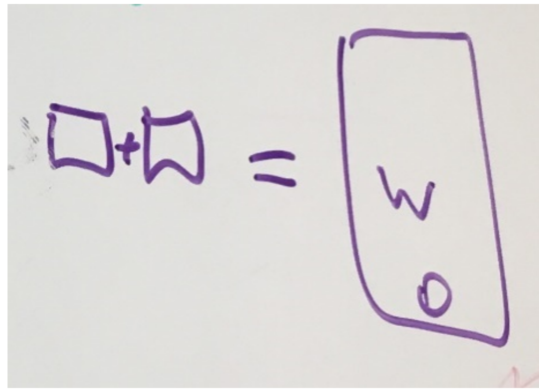


Figure 26 Every product has associated waste

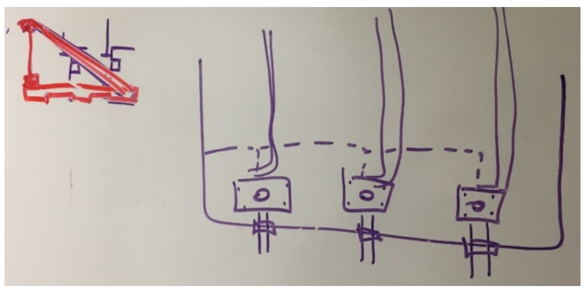


Figure 27 Constructed On-site Unit vs Packaging Pellet + Prefabricated Unit

Operation savings is more than material savings. The fuel to transport, the crane to lift it up, and the labor to move it around. And consider you are moving it in and out, so 15% of extra material becomes 15% in + 15% out = 30% resources. Subcontractors usually use 15% material waste for hauling cost estimate.

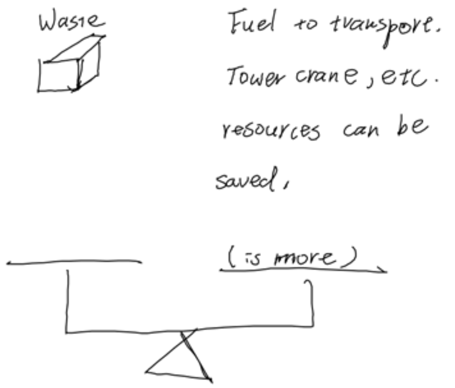


Figure 28 Operation savings is more than material savings

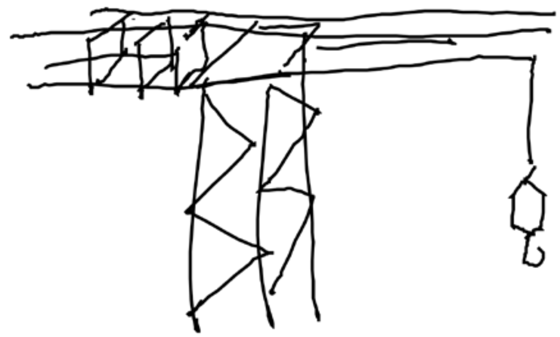


Figure 29 It takes resources to move extra materials

4.2 Solutions

Standardized Dimension

Use standardized dimension for design; for example, drywall comes in 4' × 8', design the room so the dimension is in multiply of 4', like 12' wide, 20' wide, or if the room is 18' wide, the other half of the drywall can be used for another room; or design the room to be 8’ tall and the studs can also be ordered to length. This is called ‘informed design.’

Figure 30 Use standardize dimension

Prefabrication

The guy doing (building) it is the greatest resources. Plumbing foreman initiated putting wall-hung water closet with piping in struts so they can just bring the set to the site and anchor it down with a few expansion bolts, without bothering working around the metal studs, and kneeling down on the floors. They know what they can do, what can be more efficient, and want to continue improving it.

A hospital renovation job had both upper and lower floors still in operation. With coordinated multi-trade service racks in the corridors, it only need 120 anchor points, compare to 900 anchor points for pipe hangers, duct, electrical conduits, and cable tray supports.

Besides curtain wall, there is now prefabricated exterior panels. The top and bottom tracks are still installed on the floor slabs, but the drywall, vertical studs, insulation and claddings are prefabricated as one piece in the shop. When install on-site, the studs go into the top and button tracks, and 2' gap are left between panels of different floors for flashing and filler panels. The prefabrication saves metal studs, drywalls, insulation, and the drywalls are cut by CNC machines. Not only the materials are being used more efficiently, but also saved from weather damage. Plus, the fabrication shop is located in Woodville, WA for a reason, because that is where the suppliers are, so the drywalls travels only from one shop to shop locally.

Other drywall part can be prefabricated, too. An example is soffit around steel beams and columns, it can be built by CNC machines, which could avoid the tapings. Taping and other works can build up materials, it gets down to the predictability. If all the corners and miters are in 90° angle, it improves the level of predictability.

There are other parts in a building that can be prefabricated, such as structural steel, metal decking, metal studs ordered to length, mechanical equipment's packaged on skids, electrical panel for apartments come with wire pre-cut to length, ceiling light comes prewired with metal jacket, roofing come in panels, door comes pre-hung with hardware and even landscape sod can come in ready to be used.

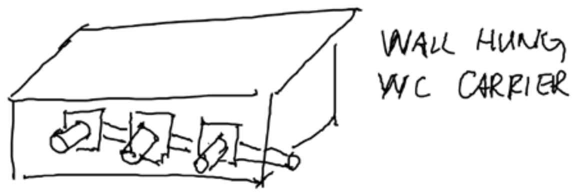


Figure 31 Plumbing foreman initiated put water closets onto struct

Figure 32 Multi-trade racks use less anchor points

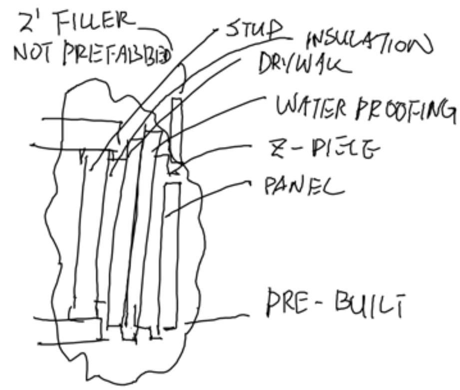


Figure 33 Prefabricated Exterior Panel

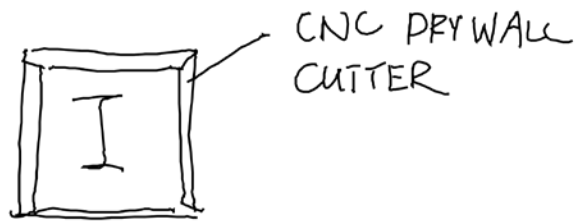


Figure 34 Drywall soffit around beams made by CNC machine

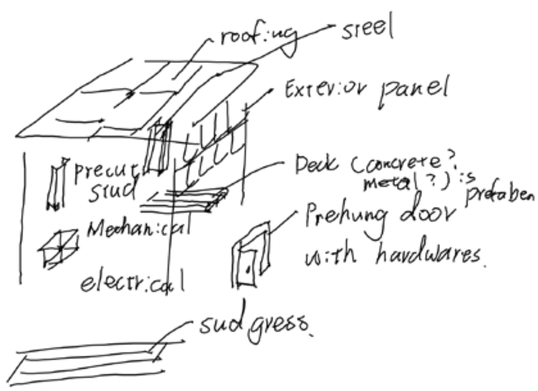


Figure 35 Many parts in a building can be prefabricated

Prefab job site so clean that there was no waste around. Superintendent hired labor (for cleaning) that has nothing to do. Typical project of 5 to 7 dumpsters/week vs. prefab project of 1 to 1-1/2 dumpsters/week. The concept of '0' zero waste can be achieved through detailed planning.

So everything was planned, even the packaging.

The superintendent must consider the work sequencing. No overhead stuff can be done, and no carpet can be worked.

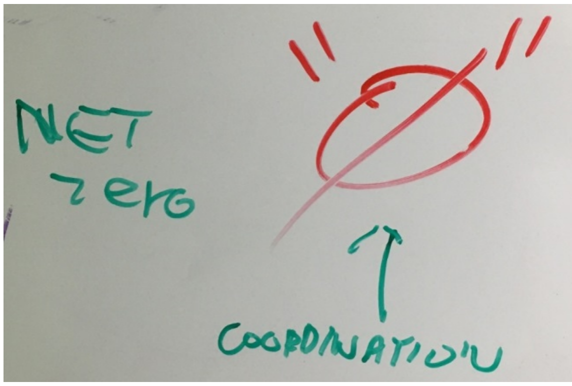


Figure 36 Zero waste

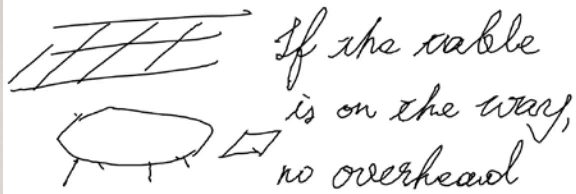


Figure 37 Prefabrication solves sequence problems

4.3 Owner’s Role

Another thing learned is owner's power and owner’s role. Owners had requested standardized dimensions be used in the design on projects, and had the right to make the requests; in the end, owner is the one who pays for the projects and the services. When owner is pushing for prefabrication, in order to get subcontractors on-board, it has to be economical to them. Owner also has a role as coordinator. As mentioned, that each contractor is good in their area of expertise. As everyone can prefab their own system, owner has a role to unify that effort. An example given was multi-trade racks. A multi-trade rack is way more efficient then mechanical puts all his piping on struts, with ductwork on its own, and electrical puts his conduits on structs, and run the cable tray by itself. Another example, is if electrical install his cable tray coming out of shaft before everybody else, mechanical would have a very hard time to fit his ductwork in. And the owner would rather pay electrical the cost of two turns, than pay mechanical the cost of a lot elbows.

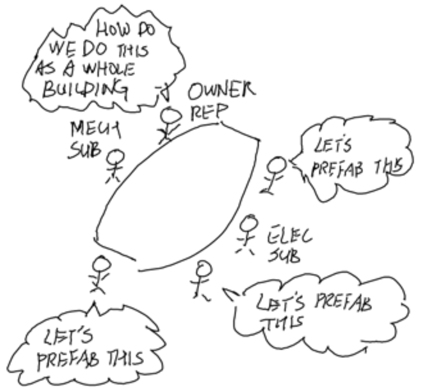


Figure 38 Coordinate prefabrication as a whole building

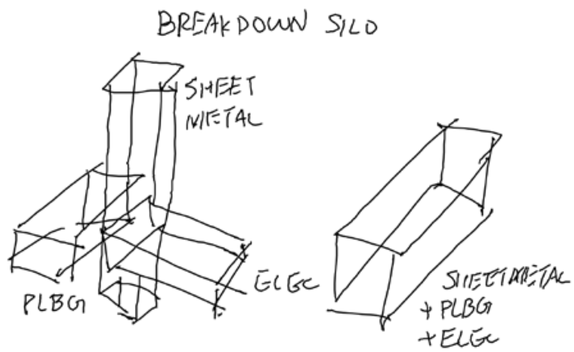


Figure 39 Breakdown the silos

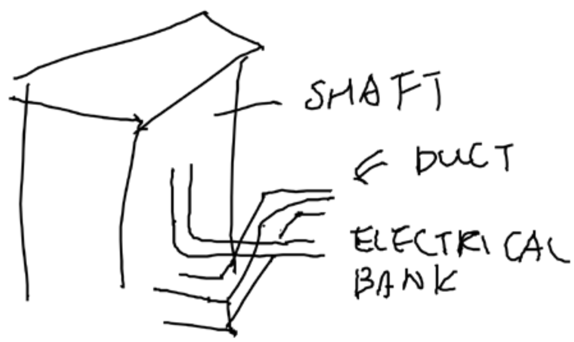


Figure 40 Coordination

5. Case Studies

Five projects were selected for case study; one hospital, two office buildings and two apartment buildings. The hospital and the offices were selected simply because their data were available. The two apartments were selected because they are residential projects; with the other three nonresidential projects, give a more complete picture for the case study on general building stocks. The first three can be used to compare to EPA's nonresidential average rate, the last two can be used to compare EPA's residential average rate. All five projects were primary data, i.e. first-hand, unpublished data, that were made available to this study. Agreements had been made to keep the projects anonymous. All five have a clear record of actual waste weight and project square footage. When reviewing the literature, only the two EPA's studies were found that provided projects' waste weight and square footage data. [2] [4] Therefore, all five projects were put in this report. Each project employed various degree of BIM and prefabrication, some did not use any. It is expected that the results from analyzing these case studies will show quantitatively, if prefabrication and BIM reduce construction waste, and how much was reduced.

5.1 Case Study – Hospital 1

Project Description

Hospital 1 is a nine-story hospital building, which is an addition to an existing hospital campus. It has operating rooms and patient beds and other services.

Life cycle inventory analysis data collection sheet

<table>
<tr><td colspan="3">Completed by: Shen-Hua Wu</td><td>Date of completion: 2/18/2017</td></tr>
<tr><td colspan="2">Unit process identification:
Waste Report</td><td>Project area:
252,000 ft²</td><td>Reporting location:
Case Study – Hospital</td></tr>
<tr><td>Emissions to land a</td><td>Units</td><td>Quantity</td><td>Description of sampling procedures
(attach sheets if necessary)</td></tr>
<tr><td>Commingle</td><td>Ton</td><td>1,410</td><td>Hauling company report</td></tr>
<tr><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="4">Describe any unique calculations, data collection, sampling, or variation from description of unit process functions (attach additional sheets if necessary).</td></tr>
<tr><td colspan="4">a For example: municipal solid waste (please list compounds included in this data category).</td></tr>
</table>

Prefabrication component selection recording sheet

<table>
<tr><td colspan="3">Completed by: Shen-Hua Wu</td><td>Date of completion: 2/18/2017</td></tr>
<tr><td colspan="2">Unit process identification:
Waste Report</td><td>Project area:
252,000 ft²</td><td>Reporting location:
Case Study – Hospital</td></tr>
<tr><td>Prefabrication Item</td><td>Units</td><td>Quantity</td><td>Description of selection procedures
(attach sheets if necessary)</td></tr>
<tr><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td></td></tr>
</table>

Waste source

The waste weight came from the total waste record. Construction detail for this project is not known. It was assumed that the project used typical construction methods, and had waste from cutting stock dimension materials, concrete and rebar waste and packaging materials.

BIM and prefabrication use and effect

BIM was used to coordinate mechanical, electrical and plumbing services. As discussed in the interview section, the coordination would save the project from interference and re-work related wastes.

Waste generate rate calculation

To calculate the waste generation rate. EPA took the sum of sampling projects' waste weight, divided it by the sum of the projects' square footage. [2] Following this method. The waste generation rate of this case study can be calculated as:

$$1{,}410\ tons = 2{,}820{,}000\ lb$$

$$2{,}820{,}000\ lb \div 252{,}000\ ft^2 = 11.19\ lb/ft^2$$

The waste generate rate for Case Study – Hospital 1 is 11.19 lb/ft^2

5.2 Case Study – Office 1

Project Description

Office 1 is a typical mid-rise commercial office building. It has a mixed stone and glass façade.

Life cycle inventory analysis data collection sheet

Completed by: Shen-Hua Wu			**Date of completion:** 2/18/2017
Unit process identification: Waste Report		**Project area:** 154,000 ft²	**Reporting location:** Case Study – Office 1
Emissions to land a	**Units**	**Quantity**	**Description of sampling procedures** (attach sheets if necessary)
Commingle	Ton	907	Hauling company report
Describe any unique calculations, data collection, sampling, or variation from description of unit process functions (attach additional sheets if necessary).			
a For example: municipal solid waste (please list compounds included in this data category).			

Prefabrication component selection recording sheet

Completed by: Shen-Hua Wu			**Date of completion:** 2/18/2017
Unit process identification: Waste Report		**Project area:** 154,000 ft²	**Reporting location:** Case Study – Office 1
Prefabrication Item	**Units**	**Quantity**	**Description of selection procedures** (attach sheets if necessary)

Waste source

The waste weight came from hauling company reports. Construction detail for this project is not known. It was assumed that the project used typical construction methods and have typical wastes.

BIM and prefabrication use and effect

It is not known if any BIM or prefabrication was used on this project.

Waste generate rate calculation

The waste generation rate for Office 1 can be calculated as:

$$907\ tons = 1{,}814{,}000\ lb$$

$$1{,}814{,}000\ lb\ \div\ 154{,}000\ ft^2\ = 11.78\ \ lb/ft^2$$

The waste generate rate for Office 1 is 11.78 lb/ft²

5.3 Case Study – Office 2

Project Description

Office 2 is a low-rise, but large floor area commercial office building. It has a mixed stone and glass façade. The construction waste in the record also included the waste from a nearby parking garage.

Life cycle inventory analysis data collection sheet

Completed by: Shen-Hua Wu			**Date of completion:** 2/18/2017
Unit process identification: Waste Report		**Project area:** 360,000 ft² office, 200,000 ft² garage	**Reporting location:** Case Study – Office 2
Emissions to land a	**Units**	**Quantity**	**Description of sampling procedures** (attach sheets if necessary)
Commingle	Ton	658.33	Hauling company report
Describe any unique calculations, data collection, sampling, or variation from description of unit process functions (attach additional sheets if necessary).			
a For example: municipal solid waste (please list compounds included in this data category).			

Prefabrication component selection recording sheet

Completed by: Shen-Hua Wu			**Date of completion:** 2/18/2017
Unit process identification: Waste Report		**Project area:** 360,000 ft² office, 200,000 ft² garage	**Reporting location:** Case Study – Office 2
Prefabrication Item	**Units**	**Quantity**	**Description of selection procedures** (attach sheets if necessary)
Steel beams and columns			
Exterior panels			

Waste source

It was possible to have concrete waste from foundation, concrete floors, and parking garage work.

Interior finish works could also have waste.

BIM and prefabrication use and effect

The project has prefabricated steel beams and columns, and prefabricated exterior wall panels. BIM was used for all structural steel. It was also used for coordinating underground utility services entering into the building. Use of structural steel reduced concrete and rebar waste. Use of prefabricated exterior walls reduce insulation and exterior finishes waste. BIM coordination and prefabrication also eliminated interference and re-work.

Waste generate rate calculation

The total waste weight of this project included the waste from constructing a nearby parking garage. But the office building would have more waste whereas the garage would have less. The representable waste generate would be between the two. One approach is to discount the garage, and count all waste as it was generated by the office.

$$658.33\ tons = 1{,}316{,}660\ lb$$

$$1{,}316{,}660\ lb \div 360{,}000\ ft^2 = 3.66\ lb/ft^2$$

This number is less than EPA's nonresidential average, to find out how much lower it is compared to EPA's average:

$$(4.34\ lb/ft^2 - 3.66\ lb/ft^2) \div 4.34\ lb/ft^2 \times 100\% = 15\%$$

When discounted the garage, Office 2 saved 15% of the waste compare to EPA's nonresidential average.

The other approach, is assumed that the garage is like the office building, which is not true, but it will give an idea of what is the waste generation if the waste weight is spread out over the total area.

$$1{,}316{,}660\ lb \div (360{,}000\ ft^2 + 200{,}000\ ft^2) = 2.35\ lb/ft^2$$

This is also lower than EPA average, to find out how much lower:

$$(4.34\ lb/ft^2 - 2.35\ lb/ft^2) \div 4.34\ lb/ft^2 \times 100\% = 45\%$$

A representable waste generation rate for Office 2 is between 3.66 lb/ft^2 and 2.35 lb/ft^2, and is between 15% to 45% lower than EPA nonresidential average.

*The square footage was slightly reduced to keep the project anonymous.

5.4 Case Study – Apartment 1

Project Description

Apartment 1 and the next case study Apartment 2 are similar projects. It has one-level underground parking, two levels of concrete retail/office/common spaces, and five levels of apartments that are wood frames. It has a mix of brick and metal panel façade.

Life cycle inventory analysis data collection sheet

<table>
<tr><td colspan="3">Completed by: Shen-Hua Wu</td><td>Date of completion: 3/2/2017</td></tr>
<tr><td colspan="2">Unit process identification:
Waste Report</td><td>Project area:
241,070 ft^2 apartment including 1level underground garage</td><td>Reporting location:
Case Study – Apartment 1</td></tr>
<tr><td>Emissions to land a</td><td>Units</td><td>Quantity</td><td>Description of sampling procedures
(attach sheets if necessary)</td></tr>
<tr><td>Commingle</td><td>Ton</td><td>1318.07</td><td>Hauling company report</td></tr>
<tr><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="4">Describe any unique calculations, data collection, sampling, or variation from description of unit process functions (attach additional sheets if necessary).</td></tr>
<tr><td colspan="4">a For example: municipal solid waste (please list compounds included in this data category).</td></tr>
</table>

Prefabrication component selection recording sheet

<table>
<tr><td colspan="3">Completed by: Shen-Hua Wu</td><td>Date of completion: 3/2/2017</td></tr>
<tr><td colspan="2">Unit process identification:
Waste Report</td><td>Project area:
241,070 ft^2 apartment including 1level underground garage</td><td>Reporting location:
Case Study – Apartment 1</td></tr>
<tr><td>Prefabrication Item</td><td>Units</td><td>Quantity</td><td>Description of selection procedures
(attach sheets if necessary)</td></tr>
<tr><td>Standardized dimension 8’ studs</td><td></td><td></td><td></td></tr>
<tr><td>PVC piping prefabbed at shop, glued on-site</td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td></td></tr>
</table>

Waste source

Although all vertical framings were 8-foot standardized dimension, horizontal top and bottom pieces, and window openings, etc. were still wood cut on-site, therefore, would have leftover materials. Waste also came from exterior brick façade, which were laid by hand. And typical waste from interior finishes.

BIM and prefabrication use and effect

BIM was only used in part of architectural design, and was not sufficient to reduce the waste. Use of standardized dimension of 8-foot wood studs were used. Framing around window openings also used standardized dimensions, e.g. 4 feet. These would save a lot waste as not only the studs were ordered-to-length from the supplier, but also standard size drywall could be used without further cutting. For the bathrooms in the suites, the plumbing contractor prefabricated the waste line PVC piping, including cutting the spools, fit the elbows, etc. in the shop, put the parts in a bag per room, and glued the parts and pieces together on-site. This saved piping materials, as the same 20-foot piping can be utilized to cut most spools out of it in the shop. For the electrical break panels in the suite, the electrical contractor also premeasured the wire length to each outlet, so the panels arrived on-site with loops of wires connected, and the contractor just run the wire to the outlet on-site. But this would not contribute to waste saving. Exterior metal cladding was also precut from big rolls in the shop, therefore, reduced the waste at the source.

Waste generate rate calculation

Apartment 1 has one level underground parking garage, however, the record gathered did not separate out square footage between the apartment and the garage. Therefore, the calculation has to include the garage, the waste generate rate can be calculated as:

$$1{,}318.07\ tons = 2{,}636{,}140\ lb$$

$$2{,}636{,}140\ lb/ton\ \div 241{,}070\ ft^2\ = 10.89\ lb/ft^2$$

Apartment 1 waste generate rate is 10.89 lb/ft^2

5.5 Case Study – Apartment 2

Project Description

See Apartment 1

Life cycle inventory analysis data collection sheet

<table>
<tr><td colspan="3">Completed by: Shen-Hua Wu</td><td>Date of completion: 3/2/2017</td></tr>
<tr><td colspan="2">Unit process identification:
Waste Report</td><td>Project area:
373,760 ft^2 apartment, 47,390 ft^2 garage</td><td>Reporting location:
Case Study – Apartment 2</td></tr>
<tr><td>Emissions to land a</td><td>Units</td><td>Quantity</td><td>Description of sampling procedures
(attach sheets if necessary)</td></tr>
<tr><td>Commingle</td><td>Ton</td><td>1504.51</td><td>Hauling company report</td></tr>
<tr><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="4">Describe any unique calculations, data collection, sampling, or variation from description of unit process functions (attach additional sheets if necessary).</td></tr>
<tr><td colspan="4">a For example: municipal solid waste (please list compounds included in this data category).</td></tr>
</table>

Prefabrication component selection recording sheet

<table>
<tr><td colspan="3">Completed by: Shen-Hua Wu</td><td>Date of completion: 3/2/2017</td></tr>
<tr><td colspan="2">Unit process identification:
Waste Report</td><td>Project area:
343,760 ft^2 apartment, 47,390 ft^2 garage</td><td>Reporting location:
Case Study – Apartment 2</td></tr>
<tr><td>Prefabrication Item</td><td>Units</td><td>Quantity</td><td>Description of selection procedures
(attach sheets if necessary)</td></tr>
<tr><td>Standardized dimension 8’ studs</td><td></td><td></td><td></td></tr>
<tr><td>PVC piping prefabbed at shop, glued on-site</td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td></td></tr>
</table>

Waste source

See Apartment 1.

BIM and prefabrication use and effect

See Apartment 1.

Waste generate rate calculation

Apartment 2 also has one level of underground garage, but its area is known, when discount the garage, the waste generate rate is:

$$1{,}504.51\ tons = 3{,}009{,}020\ lb$$

$$3{,}009{,}020\ lb\ \div 343{,}760\ ft^2\ =\ 8.75\ \ lb/ft^2$$

When assume garage is like apartment, that the waste weight is spread out the total area:

$$3{,}009{,}020\ lb\ \div (343760\ ft^2\ + 47390\ ft^2)\ = 7.69\ \ lb/ft^2$$

A representable waste generate rate for Apartment 2 is between 8.75 lb/ft^2 and 7.69 lb/ft^2.

6. Results & Discussions

The interview discussions show that BIM and prefabrication reduce construction waste. Many discussions in the interviews focused on the sources, like cutting stock materials, and packaging materials, and addressed the solutions of using standardized dimension in design, and using prefabrication so that materials can be cut more efficiently in shop, at the same time, reduce the amount of packing materials brought to site. And previous prefabrication project experiences showed that there is less visible waste on-site, labors hired for sweeping the site were not needed, and dump trucks came to site less frequent.

The case studies also revealed the same conclusion for nonresidential project.

Table 18 Case Study Results Summary

Case Study	Actual Generation Rate (lb/ft²)	Baseline Generation Rate (lb/ft²)	% Savings
Hospital 1	11.19	EPA Nonresidential	None
Office 1	11.78	4.34	None
Office 2	3.66 without garage 2.35 with garage		15% - 45%
Apartment 1	10.89 with garage	EPA Residential	None
Apartment 2	8.75 without garage 7.69 with garage	4.39	None

With extensive BIM coordination, construction sequence planning, use of prefabricated structural steels and prefabricated exterior panels, Case Study - Office 2 showed its waste rate is 15% to 45% less than EPA's nonresidential average, and even much higher saving when compared to Office 1.

The Case Study – Hospital 1 is hard to compare to, however, because it is a hospital which is more complex than typical projects and is expected to have more waste, therefore, it would not be comparable to EPA's nonresidential average. And no other statistic was available to make the comparison.

For the residential part, however, the conclusion is not decisive. The case studies did not show saving. The result came as a surprise. Apartment 1 and Apartment 2 both use standardized dimensions on wood framing and prefabrication on plumbing piping, in theory, their waste generation rate should be lower than EPA's residential average. Two possible reasons why the case studies did not show saving. One is that the EPA's residential average was based on 11 single family projects and 2 multi-family projects, so the sampling pool was too small. The second reason could be that, the dominating factor, the single-family project, could already have prefabricated roof trusses, so Apartment 1 and Apartment 2 using 8-foot studs may not generate enough savings when compared on square footage basis. So, in fact, the prefabrication could be saving construction waste, just that it is already in practice and has raised the bar higher.

Therefore, more consideration should be given to the hospital and multi-family projects. The effect of BIM and prefabrication on construction waste on these projects was not clear, because other historical construction waste comparison data was not available. It would be better if there were more samples of typical apartment to compare to. The Warrior Transitional Barracks and Miami Valley Hospital case studies shown in literature review also showed that BIM and prefabrication reduced construction waste.

Hospital 1 and Office 1 also raised the question if EPA's 4.34 lb/ft² nonresidential average is too low. However, the total construction and demolition waste EPA estimated is 170 million tons, and the 2003 report Table 3-1 included a statistic from seven states, accounted for 21% of US population, for 33.6 million tons of construction and demolition waste for 2003. A quick check 33.6 million tons ÷ 0.21 = 160 million tons showed that 170 million could be a reasonable estimate. The issue of nonresidential average alone can be improved with a bigger sample pool. One approach may be that City of Seattle requires projects over $30,000 to file a waste diversion report. [34] If this data is made available in the future, it can be used to identify the baseline per building type. But since it is not available, gathering voluntary data, like the EPA report itself and case studies presented in this thesis, can increase the sample pool.

Another suggestion on future studies would be include the operational saving, as learned from the interviews, operational savings is usually greater than the material savings. Warrior Transition Barracks, Miami Valley Hospital, Bernstein and Jones and ISO14001 all included operational savings, a study that include both operational and material savings may show a more complete picture of the benefits.

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