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SI: MODELING MATERIALS AND PROCESSES, IN MEMORY OF PROFESSOR JOSÉ J. GRÁCIO

Large scale additive manufacturing of eco-composites

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Abstract The evolution of additive manufacturing processes is enabling the production of parts with improved dimensional accuracy, mechanical, physical and chemical properties [1]. New materials also contribute to this trend, and in this scope, eco-composites, materials with environmental and ecological advantages, which include natural polymers, have been acquiring increased relevance [2]. The purpose of this study is to develop composite material parts manufactured from recycled thermoplastics and natural fibres, in this case, wood residues. Additive manufacturing (fused deposition modelling) will be accomplished using a robot combined with extrusion unit. The objective is to access the influence of the main manufacturing parameters, such as temperature, distance between layers or deposition speed, on the final part characteristics, especially dimensional accuracy. Reverse engineering and several material analysis techniques will be employed to achieve this goal.

Keywords Additive manufacturing · Large-Scale · HDPE · Sawdust

Introduction

The 3D printing covers a range of processes and technologies that offer a full range of resources to produce parts and products using different materials. The process of large-scale additive manufacturing, and specifically the Fused Deposition Modeling (FDM) process, has emerged due to the need of aerospace industry to develop prototypes and products of increasingly larger size [3, 4]. On the other hand, the use of composite materials in additive manufacturing processes has been growing, and recycled and reused materials represent an added value in terms of sustainability, reduced use of virgin materials and reduced prices, when compared to virgin materials [2].

Combining large scale manufacturing with the usage of composite materials, especially using natural fibers as reinforcements means two separate problems must be addressed: the size effects in FDM processing and the composite material response. There seems to be a lack of references for FDM printing of large dimension parts with polymer matrix composites combined with natural fibers. Murr studied the evolution of additive manufacturing and identifies multi-material printing and large scale products as being in constant evolution, requiring more time to be fully developed and optimized [5].Studies on the behavior of the material in 3D printing applications are limited to existing equipment and its capacity in terms of size, temperature or print speed. Industrial applications rely only on the development of solutions for specific or already tested materials [6, 7]. Wang reviewed the current (as of 2017) state of the art on 3D printing of polymer matrix composites. They identify potential development areas for industry in higher volume parts, currently not widely available. They also mention the need to widen the scope of materials to use, and especially towards sustainable materials [8]. Lee reviewed the current state of the art on Additive Manufacturing Technologies, referring to applications on smart materials, ceramics, electronics, biomaterials and composites [9]. Nevertheless, the use of natural fibers or the large-scale manufacturing are not mentioned. This indicates there is little research on this topic, as most studies keep their focus on small scales. The repeatability and consistency of the

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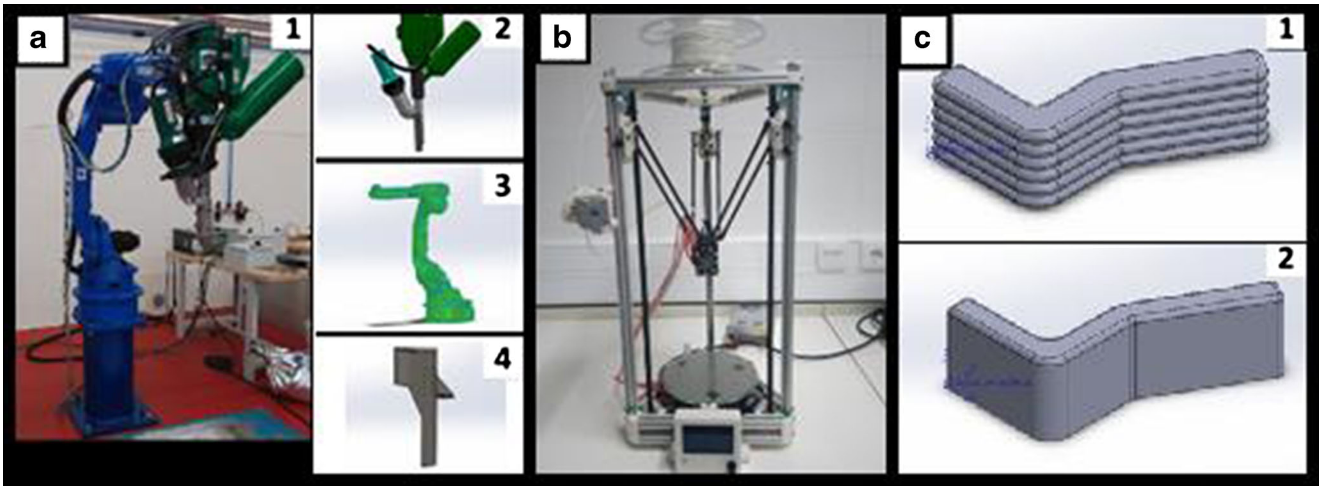

Fig. 1 Left **a**) Large-Scale FDM system (1), 3D Extruder model (2), 3D Robot Arm Model (3), 3D Coupling Device Model (4). Center **b**) Delta 3D Printer. Right **c**) CAD model for large-scale FDM system (1), CAD model for normal-scale FDM printing process (2)

processes cannot be guaranteed without ensuring the good properties of the printed materials. Therefore, both the material and the process need to be thoroughly tested.

In this work, a set of eco-composite materials obtained from reused thermoplastic matrix and natural fibers (wood residues) were developed. Test parts were produced from these materials by FDM, using an extruder mounted on a robot. For comparison purposes, parts made from ABS (acrylonitrile-butadiene-styrene) were built using the same setup. Smaller scale parts having similar geometry were built on a Deltaprintr®, calibrated for ABS processing. The goal is to validate the usage of this FDM system for the manufacturing of large-scale parts, by verifying the influence of processing parameters on part geometry, as well as comparing the results with those obtained on a 3D printer at a normal scale.

Procedure

Material A composite material composed of 45% volume of waste HDPE (high density polyethylene) recovered from the plastic injection industry and 45% sawdust from the pine logging in the timber industry was reprocessed for reuse by extrusion. An additional 10% volume of coupling agent - Dupont Fusabond® E265 - was added for increased matrix – particle adhesion [10]. The sawdust particle size is between 500 μm to 700 μm. ABS wire was used in printing by FDM in normal-scale and granulated ABS was used in the large-scale process.

Equipments A double screw extruder was used to produce the initial HDPE / sawdust composite. A high-speed single screw extruder mounted on a robot arm was combined with a heated deposition table, resulting in a large-scale FDM system –Fig. 1a). A Delta FDM 3D printing system was used to produce ABS parts at a normal scale - Fig. 1b). Simultaneous temperature analysis of composite materials was performed using STA 6000 (Perkin Elmer®) equipped with Pyris software. A portable 3D Sense® system was used for dimensional analysis of larger parts and a COMET® system was used for the smaller parts. Data processing and comparison of parts scanned with 3D CAD model were developed using Excel® software and Geomagic® Studio respectively, while the 3D model was created using Solidworks® CAD software.

Part geometry Part geometry was designed to enable the assessment of distortion in both vertical and horizontal planes, as well as shrinkage and warpage. For this work, distortion on

Table 1 Test matrix

Base Temperature	Nozzle Temperature		
	178 °C	188 °C	198 °C
60 °C	Part TM178 TB60	Part TM188 TB60	Part TM198 TB60
90 °C	Part TM178 TB90	Part TM188 TB90	Part TM198 TB90
120 °C	Part TM178 TB120	Part TM188 TB120	Part TM198 TB120

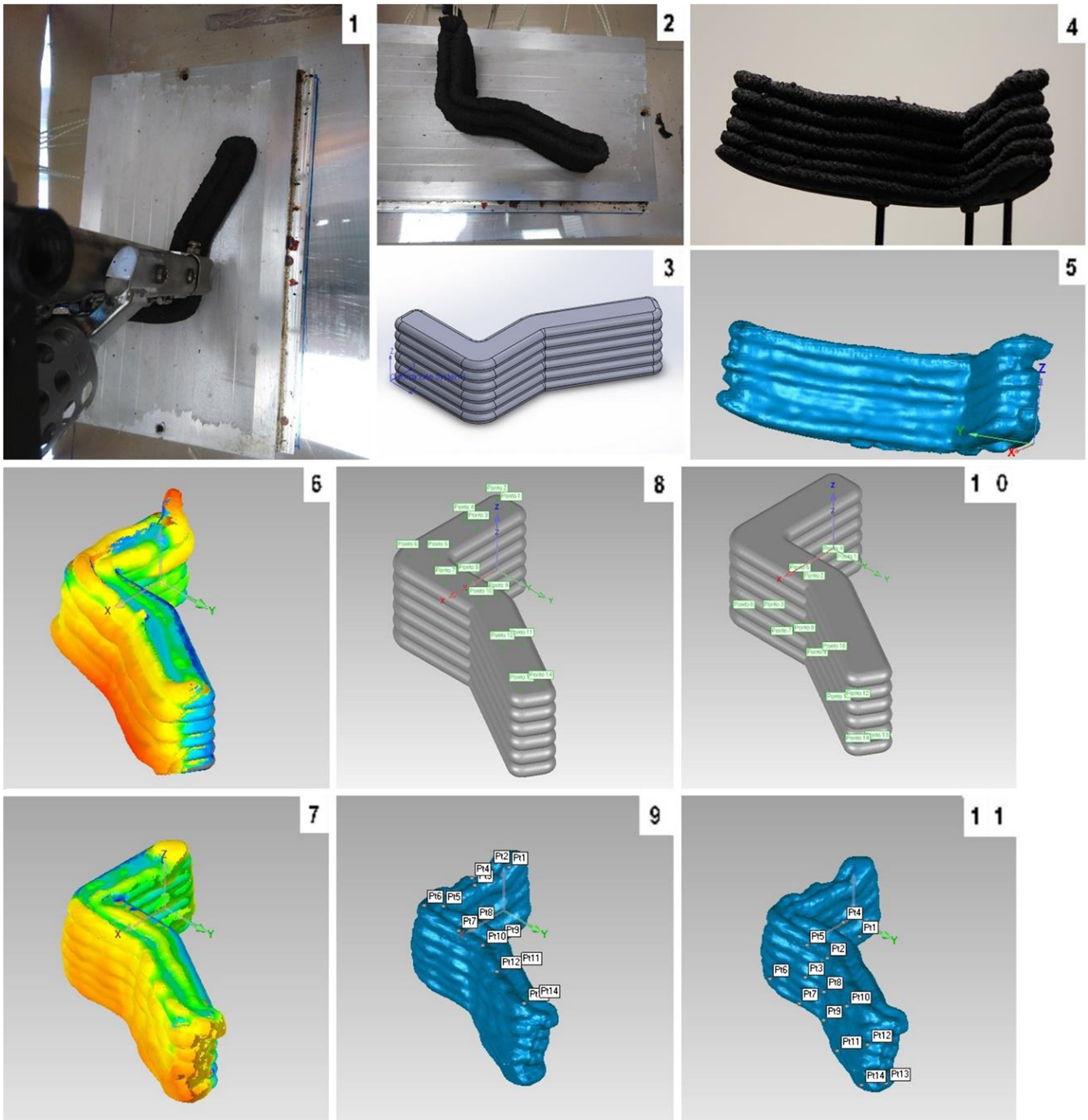

Fig. 2 3D printing (1), Printed part (2), CAD model of part (3), 3D scans (4,5), Variance analyses in Geomagic® for Part TM178 TB60(6) and Part TM198 TB120(7), measured points (8,9,10,11)

the direction perpendicular to the worktable (Z direction) is acessed. The geometry is a profile having dimensions of 30 mm width, 60 mm total height, a section forming a 90° angle with 100 mm on one side and 75 mm on the other, and another section forming a 30° angle with of 98,7 mm length. Separated 3D models for the large-scale 3D printing (**Fig.** 1c) 1) and a 3D model for the normal-scale FDM printing process (**Fig.** 1c) 2) were created.

Processing route Extruded HDPE / sawdust blend pellets were fed into the large-scale FDM system. ABS parts were also produced using this setup. For comparison, a calibrated, normal-scale FDM printing process was used to build ABS parts.

Processing parameters For the large-scale FDM system, a set of processing parameters was defined, namely the base temperature (TB) and nozzle temperature (TM), to determine their respective influence on part distortion. Three levels were defined for each temperature, which resulted in a 9-specimen test matrix - Table 1. These temperatures were defined having into account the degradation temperatures of base materials. Simultaneous temperature analysis (STA) determined a 270 °C degradation temperature for sawdust. The processing window for HDPE was determined from datasheets (maximum temperature) and preliminary extrusion tests (lowest temperature). Layer thickness and deposition speed were kept constant at 10 mm and 10 mm/s, respectively. For comparison between HDPE/Sawdust composite and ABS FDM

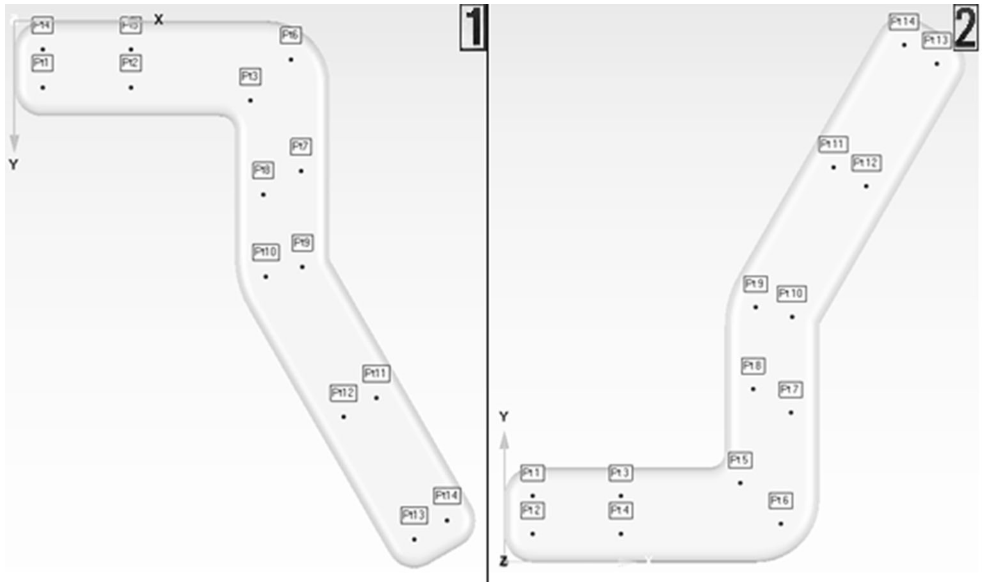

Fig. 3 Points considered for dimensional analysis: 1 - base side of part; 2 - top side of parts

processing, the same velocity and layer thickness parameters were applied. In this case, only the highest base and nozzle temperatures were chosen. For normal-scale parts, the same temperatures were kept, whereas the layer thickness was 0.3 mm and the deposition velocity was 30 mm/s.

Dimensional analysis comparison between a CAD model and experimental results accessed through 3D scanning operations was employed to determine the influence of processing parameters in parts dimensional accuracy. Figure 2 shows the sequence from the 3D printing to the acquisition of geometries by 3D scanning to obtain comparison data. The analysis comprised three stages: first, 3D scanning was perfomed for top and bottom points on both the large-scale FDM and the normal scale FDM parts. In this case, 14 points were defined in the upper and lower sides, and their Z direction coordinates were verified - Fig. 3. After this, results of the two scale 3D printing processes, using identical parts with identical parameters and materials, having a scale ratio of 1:25, were compared. Finally, an additional comparison was conducted between the ABS parts, one of the HDPE/sawdust parts and the CAD model.

Results and discussion

Data collected by Geomagic® software shows that the both base temperature and nozzle temperature influence parts warpage. For higher base temperatures, the average deviation of points on both the base and upper side of parts is reduced. For increasing nozzle temperatures, deviation does not present a linear trend –Table 2. The best results for the lower face of the part, are achieved on part TM188 TB120. A significant reduction of warpage can also be verified in the upper face. Detailed measurements show that part having the highest deviation is part TM198 TB60 on point 6, with 13,32 mm, while

Table 2 - Average deviation on parts - bottom and top side

Average Deviation on bottom side of Parts (mm)				Average deviation on top side of Parts (mm)			
TB	TM			TB	TM		
	178 °C	**188 °C**	**198 °C**		**178 °C**	**188 °C**	**198 °C**
60 °C	3,04	3,44	4,64	**60 °C**	2,81	1,74	3,41
90 °C	2,6	2,72	1,98	**90 °C**	2,48	2,73	3,1
120 °C	0,82	0,44	1,16	**120 °C**	1,98	1,89	1,3
Average deviation on bottom side of parts (%)				Average deviation on top side of parts (%)			
TB	TM			TB	TM		
	178 °C	**188 °C**	**198 °C**		**178 °C**	**188 °C**	**198 °C**
60 °C	5,07	5,73	7,73	**60 °C**	4,68	2,90	5,68
90 °C	4,33	4,53	3,30	**90 °C**	4,13	4,55	5,17
120 °C	1,37	0,73	1,93	**120 °C**	3,30	3,15	2,17

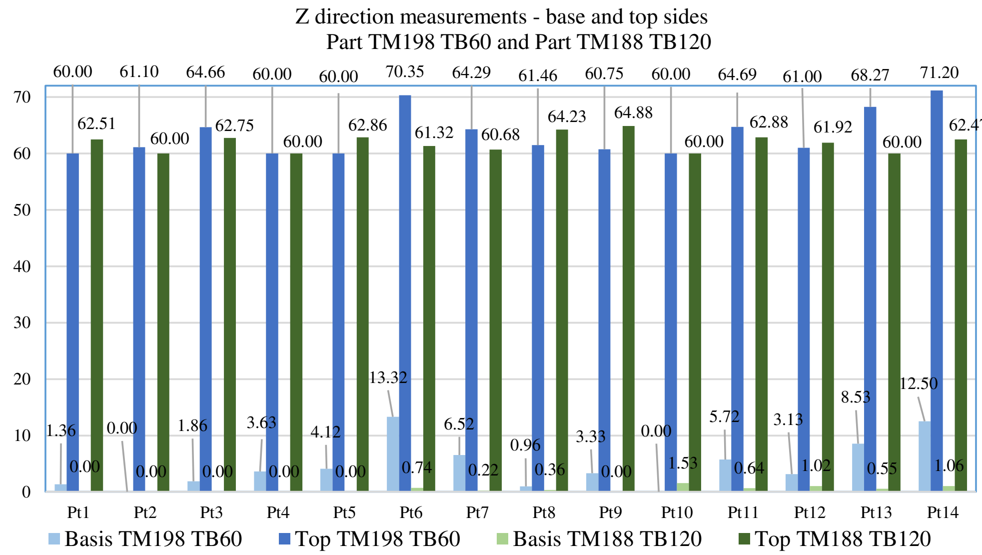

Fig. 4 Z direction measurements - base and top sides for Part TM198 TB60 and Part TM188 TB120

part TM188 TB120 presents 0,74 mm at the same point. Point 14 on part TM198 TB60 has a deviation of 12,5 mm compared to part TM188 TB120 with a value of 1,06 mm. A reduction of warpage can also be observed for those points in the case of the upper face of the part, on Fig. 4.

Table 3 Shows the comparison of deviations from CAD models between ABS parts built using the normal scale FDM printer and the large-scale FDM system, as well as between ABS and HDPE/sawdust parts, both built using the large-scale FDM system. Values were obtained after applying a scale factor on the smaller scale part, for comparison. For ABS built using the large-scale FDM system, the deviation is higher for both the bottom and top sides of the part, when compared to the same part built by the the normal scale printer. Comparing the parts built using the large-scale FDM system, it becomes evident that the differences are smaller, but nevertheless, for the HDPE/sawdust composite the error on the bottom side is twice the one observed for the ABS part. The situation is inverted for the upper side, with the ABS part displaying more than two times the relative deviation when compared to the HDPE/sawdust composite part. Since the processing temperatures and speeds used were the same, the differences observed may be due to the contraction factor of the material. ABS is known to exhibit the significant warpage behavior with increasing part size [11]. It is also noted that although in the ABS Part built using the the normal scale printer the average deviation is much lower, the standard deviation is quite similar. In parts printed with the large-scale FDM system with different materials, the standard deviation has a difference of only 0.1 mm, and hence the parts are quite identical in terms of deviations.

Conclusions

Dimensional analysis of parts built using the HDPE / sawdust composite with variation of base and nozzle temperatures shows that an increase in base temperature can be beneficial

Table 3 Geomagic® dimensional analysis between 3D printing processes and materials

Absolute average deviation bottom and top side / Absolute standard deviation of parts			
Part	Average deviation Bottom side	 Top Side	Standard Deviation
ABS - large-scale FDM(mm)	0,60	3,17	3,68
ABS - normal scale FDM(mm)	0,25	0,07	2,75
HDPE TB120 TM198 - large-scale FDM (mm)	1,16	1,30	3,78
Relative Average Deviation (%)			
Part	Bottom side		Top Side
ABS - large-scale FDM(mm)	1,00		5,28
ABS - normal scale FDM(mm)	0,42		0,12
HDPE TB120 TM198 - large-scale FDM (mm)	1,94		2,16

to the dimensional accuracy of parts. The average deviation reduces visibly when the base temperature increases from 60° to 120 °C. A base temperature of 120 °C and a nozzle temperature between 188 and 198 °C seem to be the best values to proceed testing of other parameters, resulting in dimensional deviations ranging from 1,16% to 1,3%, although standard deviations are more significant (3,78%).

Material response in terms of contraction and consequent warpage was evaluated by comparing parts printed by different scale processes, using the same material (ABS). The large scale process presents increased difficulties in obtaining an apropriate dimensional accuracy, as expected. Dimensional error is higher by an order of magnitude. Layer thickness is probably the main cause for this. This implies processing parameters should be studied further, in order to achieve values closer to the ones obtained on a normal scale 3D printing processes.

Analysis of the large scale additive manufacturing processing of ABS and HDPE / sawdust composite show dimensional accuracy results are of the same order of magnitude. This seems to indicate that this type of composites presents good potential to be processed by this route. Nevertheless, this study shows further work is needed to evolve the large-scale FDM process to the point where it becomes a valid option for manufacturing.

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References

1. Gao W, Zhang Y, Ramanujan D, Ramani K, Chen Y, Williams CB, Wang CCL, Shin YC, Zhang S, Zavattieri PD (2015) The status, challenges, and future of additive manufacturing in engineering. Comput Des 69:65–89
2. Wohlers T (2010) High-performance composites. Compos World p 1
3. Rayna T, Striukova L (2016) From rapid prototyping to home fabrication: how 3D printing is changing business model innovation. Technol Forecast Soc Change 102:214–224
4. Barnett E, Gosselin C (2015) Large-scale 3D printing with a cable-suspended robot. Addit Manuf 7:27–44
5. Murr LE (2016) Frontiers of 3D printing / additive Manufacturing : from human organs to aircraft fabrication. J Mater Sci Technol 32(10):987–995
6. Lim S, Buswell RA, Le TT, Austin SA, Gibb AGF, Thorpe T (2012) Developments in construction-scale additive manufacturing processes. Autom Constr 21(1):262–268
7. Singh S, Ramakrishna S, Singh R (2017) Material issues in additive manufacturing : a review. J Manuf Process 25:185–200
8. Wang X, Jiang M, Zhou Z, Gou J, Hui D (2017) 3D printing of polymer matrix composites : a review and prospective. Compos Part B 110:442–458
9. Lee J-Y, An J, Chua CK (Jun. 2017) Fundamentals and applications of 3D printing for novel materials. Appl Mater Today 7:120–133
10. Hillig É, Iwakiri S, Andrade MZ, Zattera AJ (2008) Caracterização De Compósitos Produzidos Com Polietileno De Alta Densidade (Hdpe) E Serragem Da Indústria Moveleira. *Soc. Investig. Florestais* 32:299–310
11. 3dprintingsolutions (2016) Comparison of mechanical properties between parts printed from ABS and PolyMaxTM PLA. *3dprintingsolutions.com*. http://www.3dprintingsolutions.com.au/Store/Australia/rvdsfpid/polymax-pla-green-175mm-750g-339. Accessed 28 Dec 2016