ASSESSING THE FEASIBILITY OF UNDERGROUND MINING OF AGGREGATES IN SOUTHERN AND EASTERN ENGLAND

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Abstract

In the future, the provision of hard rock resources suitable for aggregates may give rise to increasing levels of conflict, particularly where they coincide with attractive landscapes or other forms of land use. Consequently licenses to operate new quarries or extensions to existing quarries are likely to become increasingly difficult to obtain. The underground mining of aggregates may become both environmentally more desirable and an economic necessity to maintain security of supply.

This research examined the economic feasibility of underground mining for crushed rock aggregates in southern and eastern England, where demand for this material is high but suitable resources of pre-Permian age are absent at the surface. It sought to determine whether or not aggregates could be produced underground in the south east area of England and delivered to the local market at a cost comparable with that for surface quarries located at a greater distance.

Cost models were established for aggregates production, haulage, environmental impact mitigation, health and safety, decommissioning and restoration using four different mine output scenarios. The available geological information was re-examined to identify potential areas that may contain aggregates resources at depth.

With a discount rate of 10%, the lowest discounted cost of aggregate delivered to market determined across 31 prospect locations tested was £13.03/tonne, 19% higher than the reference of £10.97/tonne from a Leicestershire reference quarry producing 3.5 MTPA, and serving the same market. Capital expenditures for the most competitive underground aggregates mines ranged from 1.46 to 1.60 times the £92.63 million estimated for the Leicestershire reference case. Value generated by after-uses for the void created as well as rental revenues from concurrent development are subsequently taken into account.

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Introduction

This paper reports research that examined the economic feasibility of underground mining for crushed rock aggregates in the UK, but particularly in the London, South East and East of England regions (the South East area of England). These regions import substantial volumes of crushed rock, primarily from the East Midlands and South West regions, requiring relatively long transport distances to market for this bulk commodity. A key part of the research was to determine whether or not aggregate could be produced and delivered to a local market in the South East area of England from an underground aggregates operation at a cost comparable with that for production and transport of the commodity from traditional surface quarries located further afield. In essence the investigation asked – could the reduced transport costs compensate for the higher production costs underground so that underground crushed rock aggregates producers can compete with the established Leicestershire and Somerset surface quarries exporting to the South East? This paper abbreviates methodology and findings reported in full by Brown *et al.*, 2010.

Methodological outline

Geological review of potential aggregates prospects

The British Geological Survey (BGS) maintains a geological archive which includes records of most boreholes drilled in England greater than 30 m depth, and a substantial number of shallower boreholes. They also hold interpretation maps of the pre-Permian bedrock of the country and details of various investigations carried out using seismic or other geophysical technologies. The BGS also holds a database of all existing and many historical mineral extraction sites. These data were re-evaluated by BGS geologists to identify the locations, depths, and extents (where possible) of potential aggregates prospects around the high aggregates demand area of London and the South East area of England.

Screening of prospect sites

The South East area of England is densely populated, largely urbanised and hosts many areas that are subject to land use designations or protections. The locations of underground aggregates prospects identified from boreholes were considered alongside additional spatial constraints that would inhibit underground mine development such as environmental or land use designations and the locations of urban areas. Boreholes within these polygons were removed from further consideration.

The results of Geographical Information System (GIS) spatial analyses were then supported by means of virtual site visits using the Google Earth data set. These virtual site-visits also proved useful in establishing; i) the current land use so that appropriate rates for land value at the prospect sites could be determined, ii) the distance to the nearest existing rail infrastructure used for assessment of the feasibility of rail head installation which could permit both inter- and intra-region distribution of aggregate by rail, and iii) the distance between the prospect location and the M25 motorway corridor which was assumed representative of the distance aggregate would have to travel to market.

The borehole locations remaining after this screening process were referred to subsequently as 'prospects' although neither the exact location nor legal permission to work these sites was implied by usage of this term. The reader is directed to Brown et al. 2010 for full details of the locations of the boreholes, the urban and land use designation polygons. The results of the analysis are presented in Table 1.

Standard cost database

A comprehensive standard costing system was developed by the research team for capital equipment items, their maintenance and overhaul, their spares as well as additional consumable items such as tyres, lubrication, power and fuel. In addition the standard costing system also specified maintenance, overhaul and replacement schedules for each item of equipment as well as rates for workforce and management personnel of all grades. The standard costing system was based on that of Western Mine estimators guide and mining cost service (Western Mine, 2006a and 2006b) but appreciably modified to reflect UK labour rates and to isolate cash costs from non-cash costs, such as depreciation, that may otherwise been double counted in valuation calculations.

Synthesis of models for the aggregate production process

The research effort involved establishing and verifying capital and operating cost models for aggregates production, stone processing (sizing and sorting), haulage of product to market, environmental impact mitigation, health and safety, decommissioning and restoration. As the optimum production intensity (million tonnes per annum, MTPA) for underground aggregates production in the South East area of England was unknown at the outset of investigations, production and associated cost models were developed for four scales of production intensity: 0.375, 0.625, 1.250 and 3.500 MTPA corresponding to, respectively: 1,500, 2,500, 5,000 and 14,000 tonnes per day.

The production models were synthesised by drawing upon items specified in the standard costing system required in order to meet, and sustain, the specified aggregate production schedule. Surface quarry or mine specifications identified: the working patterns, values for key parameters characterising the production process (e.g. overburden depth for quarries and depth of mine for underground mines, powder factors, drill factors, advance rates, bench heights), type and number of equipment, type and number of hourly paid personnel as well as type and number of salaried personnel. Production cost models were then established by using the production model specifications and looking up the corresponding capital and operating cost rates in present in the standard costing system. Part of the production model for stone winning from surface quarries is presented in Figure 1.

Accuracy of production cost models

Once these production models, their corresponding cost models and the underpinning standard costing system were established, they were reviewed in detail for their accuracy and relevance to the UK aggregates production industry primarily by the industry partner in the project, OMYA UK Ltd, and other industry consultees. This feedback was used to modify the design specifications of the underground mine, quarry or process flow sheets, or the rates used in the standard costing system. In this way, the research team endeavoured to ensure that the production cost basis on which subsequent investigations were based, was as accurate as possible without the need for disclosure of commercially sensitive data.

Reference valuation year

The study took 2007 as the year to which all costings and valuations were referenced, primarily motivated by the easier availability of data with which to populate all cost models, land values by region and development use, and other ancillary data. Where costs were only available for years alternate to 2007, these were adjusted for the

Borehole	Lithology	Depth (m)	Thick (m)	Cover geology % Thickness					Dist to Rail (miles)	"Prospect Scale"	Haul to M25 (miles)	Landtype Purchase	Environmental Designations									
				Soil/MG	SST	DOLO	CHLK	DBASE					WHS	AONB	SPA	SAC	Ramsar	SSSI	SAM	NNR	NP	Total No.
Littlebourne	LMST_C	797	1.37	0.1	17	4	78	0	1.4	Small	42	Agricultural	n	n	n	n	n	n	n	n	n	0
Kingsdown	LMST_C	904	14.65	0.1	19	0	81	0	2.7	Large	25	Agricultural	n	n	n	n	n	n	n	n	n	0
Ringwould	LMST_C	1076	14.3	0.1	17	4	78	0	0.5	Large	53	Agricultural	n	n	n	n	n	n	n	n	n	0
Betteshanger 2DB	LMST_C	798	5.3	0.1	17	4	78	0	2.2	Small	50	Agricultural	n	n	n	n	n	n	n	n	n	0
Chslet 34DB	LMST_C	510	3.9	0.1	19	0	81	0	0.11	Small	45	Agricultural	n	n	y	y	y	y	n	y	n	5
Chislet 35DB	LMST_C	660	1	0.1	19	0	81	0	1.3	Small	45	Agricultural	n	n	n	n	n	n	n	n	n	0
Adisham	LMST_C	987	8.22	0.1	17	4	78	0	0.2	Medium	45	Agricultural	n	n	n	n	n	n	n	n	n	0
Fleet	LMST_C	582	15.84	0.1	31	0	69	0	0.9	Large	47	Agricultural	n	n	n	n	n	n	n	n	n	0
Barnsole	LMST_C	813	22.21	0.1	19	0	81	0	3.2	Large	48	Agricultural	n	n	n	n	n	n	n	n	n	0
Betteshanger BH	LMST_C	887	5.79	0.1	17	4	78	0	2.6	Small	50	Agricultural	n	n	n	n	n	n	n	n	n	0
Betteshanger 7DB	LMST_C	791	3.81	0.1	17	4	78	0	1.3	Small	52	Agricultural	n	n	n	n	y	y	n	n	n	2
Bishopsbourne	LMST_C	910	20.06	0.1	17	4	78	0	1.8	Large	44	Agricultural	n	y	n	n	n	n	n	n	n	1
Chislet Park	LMST_C	808	319.1	0.1	19	0	81	0	0.7	Very Large	45	Agricultural	n	n	n	n	n	n	n	n	n	0
Chislet 39DB	LMST_C	525	2.74	0.1	19	0	81	0	0.04	Small	44	Agricultural	n	n	y	y	y	y	n	y	n	5
Chitty	LMST_C	344	269.8	4	15	0	81	0	1	Very Large	45	Agricultural	n	n	n	n	n	n	n	n	n	0
Ebbsfleet	LMST_C	353	70.01	6	20	0	74	0	0.6	Very Large	52	Industrial	n	n	y	y	y	y	n	n	n	4
Elham	LMST_C	698	17.37	0.1	17	4	78	0	4	Large	43	Agricultural	n	y	n	n	n	n	n	n	n	1
Harmansole	LMST_C	387	7.92	0.1	17	4	78	0	2.9	Medium	41	Agricultural	n	y	n	n	n	n	n	n	n	1
Little Duskin	LMST_C	686	16.39	0.1	21	8	70	0	4.2	Large	43	Agricultural	n	y	n	n	n	n	n	n	n	1
Lydden Valley	LMST_C	597	20.72	0.1	19	0	81	0	0.4	Large	54	Agricultural	n	n	y	n	y	y	n	n	n	3
Meggot Farm	LMST_C	1339	10.18	0.1	17	4	78	0	4.4	Medium	49	Agricultural	n	y	n	n	n	n	n	n	n	1
Mattice Hill	LMST_C	625	7.31	0.1	19	0	81	0	0.3	Small	57	Agricultural	n	n	n	n	y	y	n	n	n	2
Oxney	LMST_C	1128	12.19	0.1	18	1	80	0	0.5	Medium	52	Agricultural	n	y	n	n	n	n	y	n	n	2
Paddlesworth Court	LMST_C	1129	11.79	3	20	2	75	0	1.8	Medium	45	Agricultural	n	y	n	n	n	n	n	n	n	1
Ripple	LMST_C	966	45.11	0.1	20	4	76	0	1	Very Large	53	Agricultural	n	n	n	n	n	n	n	n	n	0
Rushbourne	LMST_C	424	312.6	0.1	32	0	68	0	2.4	Very Large	43	Agricultural	n	n	n	n	n	y	n	n	n	1
Stodmarsh	LMST_C	654	35.66	0.1	19	1	80	0	1	Very Large	44	Agricultural	n	n	n	n	n	n	n	n	n	0
Tollgate	LMST_C	509	8.91	2	15	0	83	0	0.6	Medium	53	Agricultural	n	n	n	y	n	y	n	n	n	2
Trapham	LMST_C	846	135.33	2	23	11	64	0	1.6	Very Large	45	Agricultural	n	n	n	n	n	n	n	n	n	0
Walmestone	LMST_C	694	2.74	0.1	19	0	81	0	3.7	Small	47	Agricultural	n	n	n	n	n	n	n	n	n	0
Woodnesborough	LMST_C	799	3.65	0.1	20	3	77	0	2.1	Small	50	Agricultural	n	n	n	n	n	n	n	n	n	0
Bletchley	GRANITE	115	9	0.1	74	26	0	0	0.1	Small	31	Industrial	n	n	n	n	n	n	n	n	n	0
Bicester	VOLC	386	128	0.1	51	49	0	0	0.4	Very Large	35	Industrial	n	n	n	n	n	n	n	n	n	0
Withycombe Farm	VOLC	1034	29	0.1	89	11	0	0	2	Large	79	Agricultural	n	n	n	n	n	n	n	n	n	0
Byfield	VOLC	773	11	0.1	89	11	0	0	8	Small	53	Agricultural	n	n	n	n	n	n	n	n	n	0
GH10	QTZT	275	12	0.1	82	18	0	0	8.5	Medium	55	Agricultural										
GST2	VOLC	253	16	0.1	92	8	0	0	1.6	Medium	60	Agricultural	n	n	n	n	n	n	n	n	n	0
Upwood	VOLC	191	23	0.6	25	74	0	0	2.4	Medium	50	Agricultural	n	n	n	n	n	y	n	y	n	2
Warboys	VOLC	170	46	0.8	26	73	0	0	3.9	Very Large	46	Agricultural	n	n	n	n	n	n	y	n	n	1
Steeple Aston	BASA	611	165	0.1	89	11	0	0	1.3	Very Large	43	Agricultural	n	n	n	n	n	n	n	n	n	0
Burnt Hill	BASA	1049	123	0.1	43	13	44	0	4.5	Very Large	29	Agricultural	n	y	n	n	n	n	n	n	n	1
Aston Tirrold	BASA	614	86	0.1	85	14	0.8	0	0.8	Very Large	29	Agricultural	n	y	n	n	n	n	n	n	n	1
Strat B1	DOLR	746	5	1	57	9	33	0	0.03	Small	24	Agricultural	n	n	n	n	n	n	n	n	n	0
Akeman Street	DOLR	350	31	0.1	77	23	0	0	2.9	Very Large	37	Agricultural	n	n	n	n	n	n	n	n	n	0
Northbrook	BASA	498	19	0.1	86	14	0	0	3	Medium	42	Agricultural	n	n	n	n	n	n	n	n	n	0
Milton	DOLR	720	100	0.1	95	5	0	0	2.8	Very Large	46	Agricultural	n	n	n	n	n	n	n	n	n	0
Warkworth	BASA	665	8	0.1	94	6	0	0	0.5	Small	47	Agricultural	n	n	n	n	n	n	n	n	n	0
Overthorpe Rd	BASA	715	14	0.1	96	4	0	0	0.8	Small	48	Industrial	n	n	n	n	n	n	n	n	n	0
Calvert East	VOLC	174	1	0.7	76	23	0	0	0.05	Small	37	Agricultural	n	n	n	n	n	n	n	n	n	0
Sonning Eye	BASA	593	48	0.2	67	5	28	0	1.3	Very Large	19	Industrial	n	n	n	n	n	n	n	n	n	0
Old Barn	BASA	779	36	0.1	96	4	0	0	2.6	Large	49	Agricultural	n	n	n	n	n	n	n	n	n	0
Ells Farm	BASA	903	8	0.1	97	3	0	0	3.9	Small	50	Agricultural	n	n	n	n	n	n	n	n	n	0
Vicarage Farm	VOLC	517	6	0.1	88	12	0	0	0.6	Small	42	Agricultural	n	n	n	n	n	n	n	n	n	0
Oxendon Hall	VOLC	232	15	0.5	86	13	0	0	2.4	Medium	55	Agricultural	n	n	n	n	n	n	n	n	n	0
Orton	VOLC	218	22	0.1	86	14	0	0	3.5	Medium	50	Agricultural	n	n	n	n	n	n	n	n	n	0
Hollies Barn	VOLC	934	61	0.1	97	3	0	0	5	Very Large	48	Agricultural	n	n	n	n	n	n	n	n	n	0
Hollowell	VOLC	336	24	0.1	91	9	0	0	3.4	Medium	55	Agricultural	n	n	n	n	n	n	n	n	n	0
Cottage Homes	VOLC	192	3	14	86	0	0	0	1.9	Small	68	Agricultural										
Crouch Farm	BASA	879	4	0.1	97	3	0	0	2.9	Small	52	Agricultural	n	n	n	n	n	n	n	n	n	0
Brickhouse Farm	BASA	776	15	0.1	96	4	0	0	3	Large	53	Agricultural	n	n	n	n	n	n	n	n	n	0
Bodicote	DOLR	738	17	0.1	97	3	0	0	0.8	Large	51	Agricultural	n	n	n	n	n	n	n	n	n	0
Brightling	LMST_J	708	148						2.9	Very Large	26	Agricultural	n	y	n	n	n	n	n	n	n	1

Table 1. *Results of urban areas and land use designation screening.*

Geological abbreviations: LMST_C – Carboniferous limestone, GRANITE – Granite, QTZT – Quartzite, BASA – Basalt, DOLR- Dolerite, LMST_J – Jurassic limestone, VOLC – Volcanic, Soil/MG – Soil / Made Ground, SST – Sandstone, DOLO – Dolomite, CHLK – Chalk, DBASE – Diabase.

Landuse abbreviations: WHS – World Heritage Site, AONB – Area of Outstanding Natural Beauty, SPA – Special Protection Area, SAC – Special Area of Conservation, Ramsar - , SSSI – Site of Special Scientific Interest, SAM – Scheduled Ancient Monument, NNR – National Nature Reserve, NP – National Park.

Prospect Scale meanings: Small <= 50 million tonnes; 50 < Medium <= 90 million tonnes; 90 < Large <= 150 million tonnes; Very Large > 150 million tonnes.

Quarry		**Daily Production**											
Daily Production:		**1,500**	**1,500**	**1,500**	**2,500**	**2,500**	**2,500**	**5,000**	**5,000**	**5,000**	**14,000**	**14,000**	**14,000**
Characteristics	**Strip**	**0**	**1.5**	**3**	**0**	**1.5**	**3**	**0**	**1.5**	**3**	**0**	**1.5**	**3**
Daily production rate	tonnes	1,500	1,500	1,500	2,500	2,500	2,500	5,000	5,000	5,000	14,000	14,000	14,000
Hourly production rate	tonnes	188	188	188	278	278	278	500	500	500	1,400	1,400	1,400
Annual production	kT	375	375	375	625	625	625	1,250	1,250	1,250	3,500	3,500	3,500
Shifts per day:		1	1	1	1	1	1	1	1	1	1	1	1
Workinghours / shift:	hours	8	8	8	9	9	9	10	10	10	10	10	10
Workingdays / year:	days	250	250	250	250	250	250	250	250	250	250	250	250
Life Of Mine (LOM):	years	20	20	20	20	20	20	20	20	20	20	20	20
Mineable reserve	MT	7.5	7.5	7.5	12.5	12.5	12.5	25.0	25.0	25.0	70.0	70.0	70.0
Drill and Blast Specifications													
Bench height (stone)	metre	15	15	15	15	15	15	15	15	15	15	15	15
Blast size	tonnes	10,000	10,000	10,000	12,000	12,000	12,000	12,000	12,000	12,000	15,000	15,000	15,000
Powder factor	kg/tonne	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Drill factor	m/tonne	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Blasthole diameter	metres	0.115	0.115	0.115	0.115	0.115	0.115	0.125	0.125	0.125	0.125	0.125	0.125
Blasthole spacing	metres	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
Blasthole burden	metres	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
Insitu rock density	kg/m³	2,650	2,650	2,650	2,650	2,650	2,650	2,650	2,650	2,650	2,650	2,650	2,650
Rows per blast	No.	2	2	2	2	2	2	2	2	2	3	3	3
Production faces	No.	1	1	1	1	1	1	2	2	2	2	2	2
Powder density	kg/m³	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
Drill bit life	metres	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
Pre-Production Development													
Ultimate Pit Area	hectare	25	25	25	50	50	50	100	100	100	100	100	100
Pre Strip Area	hectare	12.5	12.5	12.5	25.0	25.0	25.0	50.0	50.0	50.0	50.0	50.0	50.0
Pre Strip Depth	metres	0	1.5	3	0	1.5	3	0	1.5	3	0	1.5	3
Pre-Strip Volume	m³	0	187,500	375,000	0	375,000	750,000	0	750,000	1,500,000	0	750,000	1,500,000
Preproduction Mass	tonnes	0	375,000	750,000	0	750,000	1,500,000	0	1,500,000	3,000,000	0	1,500,000	3,000,000
Initial Haul Roads	meter	282	262	282	399	399	399	564	564	564	564	564	564
Initial Equipment													
Hydraulic Shovels	no							1	1	1	2	2	2
	type							E0168	E0168	E0168	E0170	E0170	E0170
Front-end Loaders	n°	1	1	1	1	1	1	2	2	2	1	1	1
	type	E0133	E0133	E0133	E0133	E0133	E0133	E0134	E0134	E0134	E0134	E0134	E0134
Rear-dump Trucks	n°	2	2	2	4	5	5	6	6	6	7	7	7
	type	E0259	E0259	E0259	E0261	E0261	E0261	E0261	E0261	E0261	E0261	E0261	E0261
Percussion Drills	n°	1	1	1	1	1	1	2	2	2	2	2	2
	mm	E0077	E0077	E0077	E0077	E0077	E0077	E0077	E0077	E0077	E0077	E0077	E0077
Bulldozers	n°		1	1		1	1		1	1		1	1
	type		E0188	E0188		E0188	E0188		E0188	E0188		E0188	E0188
Graders	n°			1			1	1	1	1	1	1	1
	type			E0094			E0094	E0094	E0094	E0094	E0094	E0094	E0094
Hydraulic Shovels	n°		1	1		1	1		1	1		1	1
(stripping)	type		E0007	E0007		E0007	E0007		E0009	E0009		E0009	E0009
Articulated Trucks	n°		1	1		1	2		1	2		1	2
(stripping)	type		E0247	E0247		E0247	E0247		E0247	E0247		E0251	E0251
Water Tankers	n°	1	1	1	1	1	1	1	1	1	1	1	1
	type	E0239	E0239	E0239	E0239	E0239	E0239	E0239	E0239	E0239	E0239	E0239	E0239
Service/Tyre Trucks	n°	1	1	1	1	1	1	1	1	1	1	1	1
	type	E0234	E0234	E0234	E0234	E0234	E0234	E0234	E0234	E0234	E0234	E0234	E0234
Powder Truck	n°				1	1	1	1	1	1	1	1	1
	type				E0238	E0238	E0238	E0238	E0238	E0238	E0238	E0238	E0238
Primary Crusher	n°	1	1	1	1	1	1	1	1	1	1	1	1
	type	P0224	P0224	P0224	P0224	P0224	P0224	P0224	P0224	P0224	P0224	P0224	P0224
Primary Crusher Motor	n°	1	1	1	1	1	1	1	1	1	1	1	1
	type	BU0229	BU0229	BU0229	BU0229	BU0229	BU0229	BU0229	BU0229	BU0229	BU0229	BU0229	BU0229
Light Plants	n°												
	type												
Pumps	n°				2	2	2	2	2	2	2	2	2
	type				P0006	P0006	P0006	P0006	P0006	P0006	P0006	P0006	P0006
Pickup Trucks	n°	2	2	2	3	3	3	4	4	4	7	7	7
	type	E0224	E0224	E0224	E0224	E0224	E0224	E0224	E0224	E0224	E0224	E0224	E0224
Buildings													
Workshop	m²	199	199	199	288	288	288	486	486	486	486	486	486
	type	B0081	B0081	B0081	B0081	B0081	B0081	B0081	B0081	B0081	B0081	B0081	B0081
Changehouse	m²	168	168	168	250	250	250	221	221	221	221	221	221
	type	B0087	B0087	B0087	B0087	B0087	B0087	B0087	B0087	B0087	B0087	B0087	B0087
Office	m²	100	100	100	125	125	125	160	160	160	160	160	160
	type	B0086	B0086	B0086	B0086	B0086	B0086	B0086	B0086	B0086	B0086	B0086	B0086
Stores	m²	149	149	149	194	194	194	297	297	297	297	297	297
	type	B0081	B0081	B0081	B0081	B0081	B0081	B0081	B0081	B0081	B0081	B0081	B0081
Powder Magazine	m²				11	11	11	20	20	20	20	20	20
	type				B0041	B0041	B0041	B0041	B0041	B0041	B0041	B0041	B0041
Primary Crusher House	n°	1	1	1	1	1	1	1	1	1	1	1	1
	type	B0042	B0042	B0042	B0042	B0042	B0042	B0042	B0042	B0042	B0042	B0042	B0042

Figure 1. *An illustrative extract of the production cost modelling approach: UK quarry production models for 4 distinct scales of production and 3 depths of pre-strip (metres). Text entries in 'Initial Equipment' and 'Buildings' sections are index entries to the standard cost database established for use in this study. Similar production models were developed for the underground mining methods considered in the study, see Brown et al., 2010 for details.*

effect of inflation using Office for National Statistics (ONS) cost and price indices (ONS, 2008). An auxiliary consequence of utilising 2007 as the reference year for all comparisons is that it avoids extreme values of cost variables prevalent during 2008, close to the last economic peak and also avoids 2009 values arising as a result of the recessionary economy. As a result, analyses and cost comparisons presented herein are broadly assumed to apply to a post-recession economy experiencing moderate growth.

Optimum mine design for prospect sites

Each of the remaining 'prospects' represented by the BGS boreholes passing the GIS screening process were subjected to a search procedure, based on exhaustive enumeration, to identify the mining method, stope layout, production intensity and the method of access to the sub-surface. The objective function that was used to guide the process was minimisation of the Discounted Cost of Aggregate Delivered (DCAD) to the local market, for each 'prospect'. The DCAD is the average price per tonne delivered to a client in the target market area from an operation that returns zero net present value, NPV(i%), when all relevant costs are considered. The value of the discount rate, i, adopted for the valuation calculations was 10%. The search processes were constrained by the mine life or the prospect extent at each site.

Costs considered and scheduling of capital expenditure

Computation of the DCAD required establishing a discounted cash flow valuation model that reflected the prospect conditions and applicable constraints, and assimilated and scheduled the following costs:

- Capital costs:
  - Land Procurement (adopting Valuation Office Agency regional rates)
  - Primary access development (shaft or adit, depth dependent)
  - Other mine development capital expenditure
  - Aggregate processing and load out plant capital expenditure
  - Feasibility, Permitting & Engineering (@5% of capital expenditure so far)
  - Railhead costs (location within 2 miles of rail network, production >= 5,000 tonnes/day)
  - Environmental mitigation costs
  - Decommissioning costs in the post-production phase
- Operating costs:
  - Aggregate winning from the sub-surface
  - Aggregate crushing, screening, load out
  - Contracted aggregated haulage costs (including 5% contractor gross profit margin)
  - Aggregates levy at £1.60 per tonne mined
  - Royalties (South East = £0.90 /tonne, East of England = £0.65/tonne, £0.45 elsewhere)
  - Annual aftercare costs in post decommissioning phase

Land procurement and Feasibility, Permitting and Engineering costs were presumed sunk at the start of pre-production period. Primary access development capital expenditure was scheduled over the first two years of mine development (50% of total per year) with remaining mine development capital expenditure, railhead, and environmental mitigation costs scheduled for the third and final year of pre-production development. Processing plant capital expenditure was equally allocated over each of the three pre-production years. Decommissioning costs were scheduled for the year following the cessation of aggregate production, and recurrent after care costs applied in the years following that.

Haulage transportation cost model

Under the various aggregate haulage assumptions discussed in detail in Brown et al. 2010, the unit transportation costs by transport modality as a function of haul distance adopted in the research were as illustrated in Figure 2. This aggregate haulage cost model was informed by work reported by Coyle, 2007 and from statistical data supplied by the Freight Transport Association (Freight Transport Association, 2009). The model was released to freight transport and aggregates industry professionals for comment on its accuracy and applicability. Feedback from these consultees was used to refine the model before it was used in valuation calculations.

For production intensities of 5,000 tonnes per day and prospect locations within 2 miles of the existing rail transportation network, 50% of the total aggregate production was assumed to be distributed by rail. The remaining production was assumed hauled by either 4 axle, 32 tonne gross vehicle weight, rigid bodied or 6 axle, 44 tonne gross vehicle weight articulated trucks, by road. The local market, which was assumed to comprise 20% of the total production, was taken to be served by rigid bodied trucks and the remaining volume was transported by articulated trucks. Where no railhead is available or the production intensity was lower than 5,000 tonnes per day, it was assumed that the split over articulated and rigid trucks was equal. The unit transportation cost model and the modality split assumptions were used to establish average haulage rates in the computations of the DCAD.

Stope layout design

The key technical issue of avoiding subsidence within relatively heavily populated areas of the South East area of England was also addressed. This consideration constrained the choice of mining method to pillar supported techniques only and reduced the volumetric extraction ratio of mining as pillar dimensions increased with depth for all aggregate geologies (and hence overburden stress) so that pillar strength factors of safety were at least 1.8 in all cases. The mining methods considered were thus confined to Room-And-Pillar (R&P) and Long Hole open stoping (LH). Dimensions of void created through aggregates production were related to tipping height (stope heights of 8 metres) and turning and reversing circles of mobile plant (stope widths of 14 metres) used in sub-surface aggregates production.

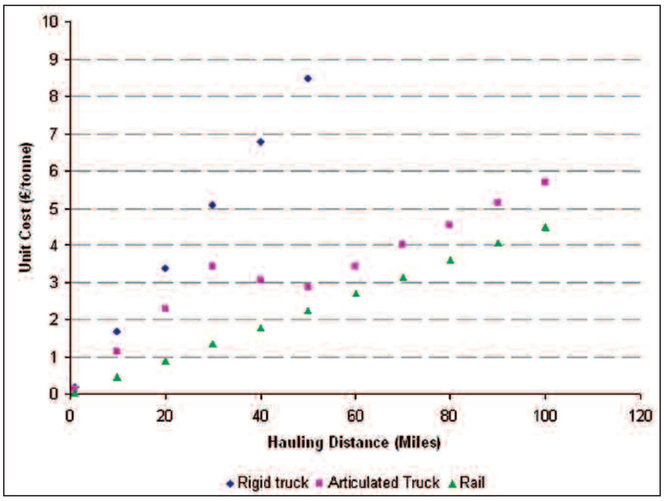

Figure 2. *Unit haulage cost for each transport modality.*

assumed to be the total site area at surface less the ultimate pit area, for surface quarries with the same production intensity. This implied that the surface foot print of an underground mine would accommodate secondary crushing and screening plant, stockpiles, waste tips, water treatment, load out, weighbridge, workshops, stores and offices.

The valuation model considered the land area procured for an underground mine as a variable that depended on whether the freehold and mineral rights above all sub-surface workings were secured. For short aggregates mine lives (~15 years) the areal extent of workings only rarely encroached on the land boundary of the surface footprint of the mine. The land area requiring procurement was determined by the areal extent of sub-surface workings in the cases of aggregates mines with either i) long mine lives and/or ii) deep workings with low volumetric extraction ratios.

Land use, value and procurement

Land use pressure is typically higher in this area of England than elsewhere so a subsequent part of the research was the identification of potential concurrent uses of land around the surface facilities of underground aggregates mines. The value, development costs for specific developments and determination of yields expected, from these uses were estimated using data published by the Valuation Office Agency, (VOA, 2007). These were also used to investigate potential economic benefits associated with after uses of remediated surface land above potential underground aggregates mines and also for the new underground space that would be created. A survey was undertaken of possible and credible after uses for the underground space created after aggregates extraction activities were completed and these are reported and discussed in full in Brown *et al.*, 2010.

Current land types of all 'prospects' passing GIS screening were predominantly agriculture with a few exemplars with industrial land use classes. The 2007 Government Valuation Office Property report (VOA, 2007) was the prime source of information on realisable land values for each of the UK regions relevant to this study and were presumed as the appropriate land procurement rates (Table 2). Statistical analysis of data contained within reports of quarry operations held within the Camborne School of Mines library demonstrated that the land take footprints of surface quarries, required to establish total land procurement cost, were found to vary with quarry production intensity as indicated Table 3. The ultimate pit plan area was also identified within these reports. The surface foot print of an underground aggregates mine with a given production intensity was

Environmental compliance costs

There may be environmental and social benefits associated with reduced noise, dust, vibration and visual intrusion of underground aggregates mines compared with surface quarries and the scope of the research accommodated attempts to quantify the relative costs of measures aimed at mitigating environmental impacts for each method of working.

Each individual location under consideration for mineral extraction will have a unique set of circumstances that will result in highly site specific environmental impacts and mitigation costs, making it very difficult to generalise. Some environmental mitigation costs were found to vary in proportion to the size of the operation (whether surface or underground), while others were found to be unrelated to this aspect. Consequently the values presented in Table 3 must be considered highly provisional. Readers interested in the full detail of the formulation, relative extents of impacts between surface quarries and underground mines, etc. are referred to Brown et al. 2010.

Decommissioning and aftercare costs

The relative scale of decommissioning, restoration and aftercare costs for underground mining may be less than those for surface quarrying as these may relate to the 'land take' of the production operation. Specific items considered in this research under the headings of decommissioning and restoration include as examples: disconnection of services and removal of static plant. In the aftercare phase, activities included maintenance of site security and planting and further, variable activities

Type	East Midlands	West Midlands	East of England	South East	South West	Inner London	Outer London
Agriculture	8,831	6,346	7,956	8,764	7,997	'-	'-
Industrial	450,000	568,000	1,119,000	1,499,000	717,000	2,285,000	2,285,000
Commercial	588,000	667,000	1,369,000	1,676,000	848,000	2,810,000	2,810,000
Retail	6,981,560	7,632,250	7,414,600	8,101,945	7,661,226	12,258,154	8,399,053

Table 2. *Land use values by land use type for selected UK regions (£/ha) (Source: VOA, 2007).*

	Production Rate (tonne/day)	Site area at surface (ha)	Mitigation of environmental impact (£)	Decommissioning (£)	Aftercare costs (£/annum)
Underground Mine	1500	20	501,160	530,500	28,000
	2500	25	569,070	777,500	30,000
	5000	35	1,161,890	1,266,500	30,500
	14000	65	1,573,690	1,830,000	46,000
Surface Quarry	1500	25	603,910	547,500	10,000
	2500	50	971,820	1,076,000	20,000
	5000	100	2,073,640	1,228,000	30,000
	14000	100	2,131,440	2,146,500	40,000

Table 3. *Summary of surface land take, and costs of mitigation of environmental impact, decommissioning and aftercare for underground mines and surface quarries with varying production intensity.*

that depended on the specific subsequent land use. The research concluded that the reality of the situation is that it is more complex than land take proportionality implies because the scale of aftercare activities depended significantly on the specific after-use identified for a particular site. Readers interested in the full detail of the formulation, relative nature and extent of decommissioning works and aftercare activities between surface quarries and underground mines, etc. are again referred to Brown *et al.* 2010.

Production cost models

Within this section, summary results from the production cost models are presented in Tables 4, 5 6 and 7, in order that the reader can perform basic comparisons with corresponding figures based on their own experiences and so that the comparative valuation methods adopted can be explained. There is insufficient space here to set out all the assumptions, relations and constraints applying to the development of the production cost models that were established as part of the research. Readers requiring all the detail are referred to Brown *at al.* 2010.

The aggregates production cost models only include the costs of mining or quarrying rock to the point that it has passed through a primary crusher either located on surface or underground (for the underground shaft hauled option). The Metso Bruno processing flow sheet design and mass balancing software (Metso, 2009) was used to establish a set of specifications and cost models for a series of generic aggregates processing plants (sensitive to wear rates expected to be typical of limestone and granite type plants) designed for increasing production rates, spanning those considered in the stone winning specifications. All costs related to processing of primary crushed material into saleable product are captured in these separate processing cost models.

Surface quarry models

The production model and equipment set up for each quarry production scenario (Figure 1) was derived from a survey of operating practice of more than 40 UK quarries, evidenced in the archived reports of quarry operations held within the Camborne School of Mines library. Face loading is typically done with use of a wheel loader serving two trucks. Increased daily production is achieved by working the loader more efficiently so that more trucks can be served, even with a longer haul distance. Scaling of the equipment upwards enhanced subsequent production capacity, but the numbers of units adopted are broadly the same. For very high production rates a hydraulic face shovel is used to handle large blasts. The number of worked benches determines the number of drill rigs and the load–haul systems. It been assumed that all equipment is owned and operated by the quarry operator. The equipment is worked up to the end of its expected useful life after which it is replaced. Expected equipment lifetimes are retrieved from equipment databases, and used to schedule replacement capital expenditure.

Surface quarry reference case

The assessment of the economic performance of a surface aggregates operation provided an objective basis for comparison with the potential underground aggregates producers. Production and production cost models for surface quarrying operations were established such that the DCAD(10%) of aggregates produced from surface quarries could be determined. The methodology applied to compute these values was identical to that for the underground mines, with values for land procurement, development etc. set to reflect the surface quarrying situation (for example: clearly, shaft development time and capital cost are set to zero). For the surface quarrying options, the aggregates processing plant was assumed complete by the end of year 2 of the project and the capital expenditure allocated across these 2 pre-production years. Revenues were assumed realised from the beginning of year 3 of these projects.

A key distinction for these valuation models was that the surface quarry location was more remote from the target market area than any of the underground operations modelled. If the DCAD(10%) for a particular underground operation is the same as for surface quarries, then this represents an indifference to an economic argument not to utilise potential underground resources, closer to market, on the basis of cost. Put another way, under these circumstances, aggregates operators would be faced with an equivalence of choice between an underground aggregates mine located fairly close to a population centre and a quarry located further way from its export demand centre.

Quarry Capital Cost				
Stripping depth (m)	Production rate (tonnes/day)			
	1,500	2,500	5,000	14,000
0.0	6,107,036	9,295,371	20,127,457	22,590,757
1.5	8,451,662	13,291,324	23,554,546	26,110,291
3.0	8,952,479	14,295,276	23,957,408	26,561,018

Table 4. *Summary of quarry total capital costs. (£)*

Quarry Unit Operational Cost				
Stripping depth (m)	Production rate (tonnes/day)			
	1,500	2,500	5,000	14,000
0.0	2.06	2.21	2.22	1.00
1.5	2.60	2.79	2.44	1.11
3.0	2.69	2.95	2.55	1.13

Table 5. *Summary of quarry operating costs (£/tonne)*

Processing Plant Capital Cost				
Plant design	Production rate (tonnes/day)			
	1,500	2,500	5,000	14,000
Limestone plant	21,427,979	21,991,986	36,403,585	50,735,080
Granite plant	24,495,637	25,059,643	40,339,223	61,569,428

Table 6. *Summary of secondary crushing, screening and load out plant capital cost (£)*

Processing Plant Unit Operating Cost				
Plant design	Production rate (tonnes/day)			
	1,500	2,500	5,000	14,000
Limestone plant	2.20	1.49	1.10	0.61
Granite plant	3.07	2.01	1.47	0.97

Table 7. *Summary of secondary crushing, screening and load out plant operating cost (£/tonne)*

The surface quarry reference case was for a quarry located 70 miles from the M25 motorway in Leicestershire, but connected to the rail distribution network and delivering 50% of output by rail to the target market area, 20% by 8 wheel, 4 axle rigid bodied trucks to the immediate market 25 miles around the site and 30% by articulating tipping trucks to customers over 25 miles around the site. The freehold of the complete site was assumed owned by the operator which obviated the need to separate mineral rights from the freehold and implied zero royalty payments to 3rd parties. The production intensity was set at 3,500,000 MTPA, placing this quarry in the so-called 'SuperQuarry' category. The thickness of overburden was assumed negligible and the quarry operating life was assumed to be 50 years. The DCAD(10%) for this case was £10.97 / tonne.

Sensitivity of the DCAD(10%) for the Reference Leicestershire 'SuperQuarry' was investigated for varying lengths of project life. The results (Table 8) indicate negligible sensitivity of the DCAD(10%) with project lives greater than 30 years, and a 6.2% higher value for a project life of 15 years (which would be considered rather short for a quarrying operation). For these reasons a value of £10.97 / tonne was adopted as a reference figure against which DCAD(10%) values arising from the underground aggregates mines could be compared.

The development capital intensity is another important metric for aggregates operators entertaining developing new crushed rock aggregates production capacity. Using the production models and production cost models developed in this research, the Reference Leicestershire 'SuperQuarry', was found to have a total development capital cost of £92.63 million (Table 9).

Underground Mine Models

Two methods of primary access to the sub-surface were considered. The first scenario deals with vertical shaft access (up to 1000 metres deep) and the second with access by means of a 10° declined adit. Each method and access type is modelled for the 4 distinct production intensities considered in the research, and is rendered sensitive to development through both wet and dry strata (implying differences in shaft sinking and pumping costs). Although the presence of water can have important impacts on ground stability, for the present study wet working conditions were not assumed to have a major impact on stoping operations.

Production Life	DCAD(10%) @ 14,000 tpd	Sensitivity against 50 year value
(years)	(£/tonne)	(%)
10	12.54	114.3
15	11.66	106.2
20	11.28	102.8
35	10.97	100.0
50	10.97	100.0

Table 8. *Sensitivity of the discounted cost of aggregate delivered (10%) for varying production life of the Reference Leicestershire 'SuperQuarry'.*

Item	CAPEX
Feasibility, Permit, Engineering	4,208,009
Land procurement	883,133
Quarry	22,590,757
Plant	61,569,428
Railhead	1,249,279
Environmental compliance	2,131,440
Total	92,632,047

Table 9. *Schedule of capital cost items for Reference Leicestershire SuperQuarry (£).*

In the development of underground aggregates mine specifications for computation of the capital costs, a working depth of the shaft or adit of 150 metres was assumed to permit summary capital and operating costs to be presented (Table 10 and Table 11). When applied to specific 'prospects' the depth of potential aggregates intersections varies and a depth dependent shaft sinking / adit development cost model is required. The method reported in the SME Mining Engineering handbook (O'Hara *et al.*, 1992) is a frequently adopted estimation method for shaft development costs, however it is fully empirically-based and also somewhat dated. Consequently effort was allocated to upgrading the O'Hara model so that at least the depth dependent cost component, could be estimated with improved confidence. The estimation model was rendered suitable for the current purposes by:

- allowing recent input costs for labour, explosives, grout, etc to be used,
- rendering the model sensitive to varying shaft geology, and;
- rendering the model sensitive to sinking through wet measures, by means of varying the advance rates, allowing for probe hole drilling, grout hole drilling and modelling grout consumption explicitly.

Fixed cost components, such as head gear and shaft equipment, were estimated using O'Hara's methods. These costs were estimated originally in 1992 US$, converted to 1992 £ using currency exchange rates applicable to 1992, and then these were corrected to 2007 terms by use of a cost indices for construction projects (Langdon, 2006).

Surface mobile plant is less specialised—and thus less expensive—than equipment designed purely for underground use (which must be able to be disassembled and slung beneath shaft cages) and was assumed adopted where primary access by decline was modelled and adit dimensions could accommodate them. For room-and-pillar mines, rubber-tyred, twin boom drilling jumbos were specified whereas single boomed drill rigs similar to those used in surface quarrying were specified for the long hole open stoping models.

The distinctions in mining methods and primary mine access type lead to further distinctions in underground mine equipment selection, site development, stope development and sub-surface mine infrastructure requirements as well as distinctions in development times and consequently the timing of mine development capital expenditure that are all considered in the research and are presented in detail in Brown *et al.* 2010, for the interested reader. Table 10 summarises the capital costs for sub-surface stone winning.

For the same production rate, variations in operating costs between the different mining methods are attributable to differences in drilling and blasting practices and the extent of stope development work required to bring stopes into a state of production. Diesel fuel consumption was calculated based on the total engine rating (which varied between methods and access type) and utilisation factors of 83% for heavy plant and 40% for light vehicles that are less intensively used (Kumar, 2007). Typically, only a few mine services have the highest share of the total electrical power consumption, these being: ventilation (with 100% load factor and total flow rate requirements dictated by the total rating of diesel engine powered plant operating underground), hoisting (for shaft access mines), pumping (for wet mines with pump rating directly related to the head and hence depth of workings, and high load factors) and aggregate primary crushing (where load factors were assumed to be equivalent to 60% of installed capacity). Table 11 summarises the operating costs for subsurface stone winning.

Results of geological review

The geology of England is such that the rocks close to the surface in the southern and eastern parts of the country are generally of Triassic or younger ages (with a maximum age of approximately 210 Ma). Most good quality hard rock aggregates come from formations of Carboniferous or older age (with a minimum age of approximately 300 Ma). However, below the younger rocks in the south-east of England, older formations can be located and it is true to say that if you go deep enough you will eventually find good quality hard rock which is likely to be suitable for use as aggregates. That said, it is clearly more expensive to mine at greater depths and some of these deeper, older rocks are likely to be too deep for an underground aggregates mine to be economic. Consequently, a maximum depth of 1000 m was used in this research when examining the geological datasets. This removes much of the area immediately around London because the thickness of younger rocks is greater than this maximum.

When searching for rock types that may potentially be suitable for use as aggregates, consideration has been given to the principal rock types that are currently worked at the surface in England. These are Carboniferous age limestone, various types of igneous

Underground Capital Cost						
Mining Options			Production rate (tonnes/day)			
			1,500	2,500	5,000	14,000
R&P	Shaft	wet	25,249,792	35,225,245	48,893,965	69,188,899
		dry	22,151,939	32,164,908	45,673,292	65,912,381
	Decline	wet	36,032,448	43,909,037	56,671,845	57,925,868
		dry	30,929,595	38,743,700	50,346,172	52,644,350
LH	Shaft	wet	34,038,519	57,200,363	84,249,831	113,205,359
		dry	30,940,664	54,140,028	81,029,161	109,560,639
	Decline	wet	39,861,424	56,318,177	77,930,383	92,580,965
		dry	34,758,573	51,152,843	72,645,969	87,188,254

Table 10. *Summary of total capital costs for underground mine models (£).*

Underground Unit Operational Cost						
Mining Options			Production rate (tonnes/day)			
			1,500	2,500	5,000	14,000
R&P	Shaft	wet	6.40	5.69	4.46	2.45
		dry	6.30	5.60	4.38	2.40
	Decline	wet	7.36	6.29	4.64	2.30
		dry	7.25	6.21	4.56	2.26
LH	Shaft	wet	12.26	11.48	8.71	4.03
		dry	12.13	11.39	8.63	3.98
	Decline	wet	10.84	10.83	7.89	3.60
		dry	10.74	10.75	7.81	3.56

Table 11. *Summary of underground aggregates mining operating costs (£/tonne).*

rocks (for example granite, basalt or andesite) and older, stronger sandstones or ‘gritstones’ (coarse grained sandstones).

It is likely that all rocks which are worked for aggregates at the surface have their equivalent in the sub-surface. However, this does not mean that the qualities of the sub-surface rocks are identical to those known as the surface. Rock formations can have considerable variation across an outcrop and it is likely that similar or greater variation will exist at depth. Deeper burial of most rock types results in a more indurated (harder) rock and consequently rock types which at the surface are too weak or friable for use as aggregates could become more suitable at depth. In some cases rocks which appear to have been deeply buried, at some point in their geological history, have subsequently been uplifted and are now located much closer to the surface, an example considered in this research is the Jurassic age limestone in the Weald Basin (approx 161 to 175 Ma).

In some boreholes ‘sonic interval velocity’ has been recorded using a ‘down hole’ sonic tool. This tool records the fluctuating velocity of sound in the rocks penetrated in microseconds per foot. These can be re-calculated as metres per second (ms-1) and the average for the identified interval can be plotted against depth. Nearly all such graphs show an increase in velocity with depth, which represents the reduction in porosity and permeability that accompanies compaction during burial. The correlation of this sonic velocity to engineering parameters would be a useful technique but requires further research. It is the measurements of sonic velocity in the Weald Basin that suggests tectonic uplift has resulted in unusually dense and low porosity Jurassic limestone at a relatively shallow depth.

An attempt has been made as part of this project to delineate areas that contain rocks in the sub-surface which may be of interest for use as aggregates. Although the skills and expertise of BGS geologists have been employed to provide this delineation, it must be borne in mind that the boundary lines of the areas shown are inferred and as a consequence will not be completely accurate. Any future project to develop a potential underground mine for aggregates would have to conduct extensive additional drilling in order to prove the existence, extent and quality of the proposed resource before progressing to a full feasibility assessment. Neither the BGS nor the Natural Environment Research Council (NERC) gives any warranty, condition or representation as to the quality, accuracy or completeness of the information contained in Figure 3, nor its suitability for any use or purpose.

Carboniferous Limestone

The limestones and dolomites of Carboniferous age (approx 359 to 326 Ma) are quarried extensively at outcrop, and have been mined underground in the past. Official figures for the extraction of limestone do not separately distinguish Carboniferous from other aged limestone, however, in 2007 more than 17 million tonnes of limestone were extracted from Derbyshire (which is likely to be exclusively Carboniferous) and more than 11 million tonnes from Somerset (which is mostly Carboniferous) (ONS, 2008). Although, these rocks extend into the subsurface, they have not been uniformly preserved. Carboniferous Limestone is found around Cambridge, Northampton and in the southern part of the Berkshire Syncline, but has been eroded from large parts of the intervening ground. The exact extents have not been proven. It is also present beneath the Coal Measures of the Kent coalfield and as a broad band extending east from the Mendips in Somerset to offshore in East Sussex. This latter band is deeper than 1000 m from the surface in most locations but rises to shallower depth in an area south of Brightling. All these potential areas of resource are shown in Figure 3.

Igneous rocks

Igneous rocks are proven to exist in several boreholes and their presence is suggested by geophysical techniques over a wide area of Berkshire and Oxfordshire. However, it should be remembered that sills of volcanic rocks can be highly variable both in thickness and depth from surface and therefore their extent vary appreciably. Furthermore, if a volcanic sill of similar thickness is more steeply dipping in one location than elsewhere, it may appear to have a smaller surface area on the map whilst actually containing the same volume of rock. Igneous rocks subcrop the Variscan unconformity in the Upwood, Warboys, possibly Bletchley boreholes and on the Islip Anticline, south of the Bicester borehole in an area close to the culmination of the London Platform (Smith, 1985). They are found at three or possibly four stratigraphic levels within the subcrop sequence: intra-Westphalian (299-315 Ma), Silurian (426-444 Ma), Ordovician (444-479 Ma) and Precambrian (>542 Ma).

Westphalian igneous rocks occur in the Berkshire-Oxfordshire Basin (syncline) e.g. in the Burnt Hill borehole as volcanics and in the Steeple Aston borehole as a sill or as separate leaves of probably the same sill. The sill was intruded into the Halesowen Formation near its base, where it overlies in different places Coal Measures, Devonian or Lower Palaeozoic rocks.

At a deeper stratigraphic level the Bicester borehole found early Silurian or Ordovician volcanics underlying Llandovery sediments (early Silurian). These rocks subcrop the Variscan unconformity beneath part of the Islip Anticline and can be mapped widely in the subsurface, to the west only, using seismic reflection data (Smith, 1987). The area stretches from Bicester nearly as

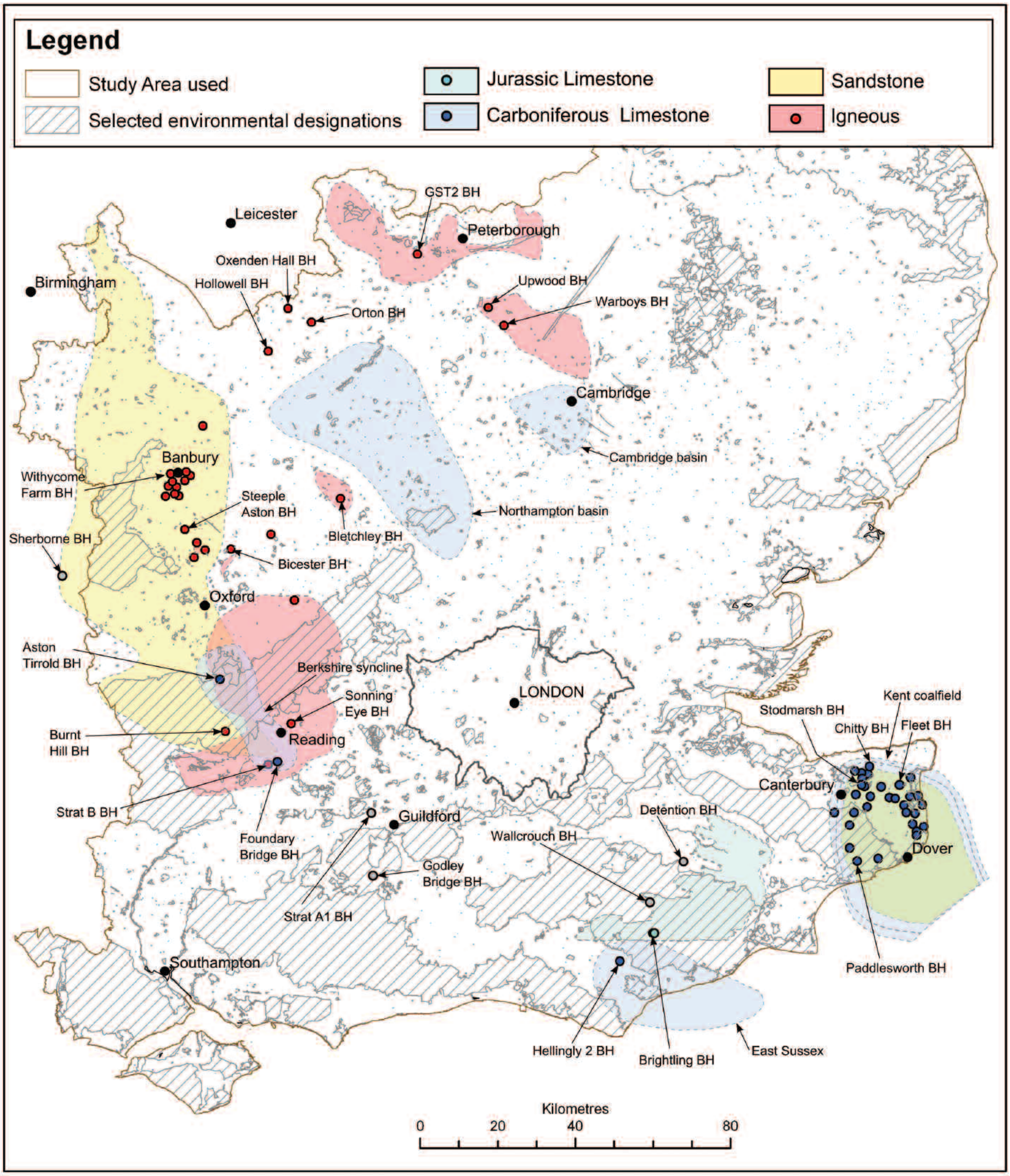

Figure 3. *Map of study area showing: i) potential areas of resource for Carboniferous Limestone (blue), igneous rocks (pink), sandstone (yellow; in the Kent area, yellow overlapping blue = olive), Jurassic Limestone (light cyan); ii) locations of deep boreholes used in the research (circles) and iii) areas with environmental or other land use designations (hatched).*

far westwards as their two outcrop areas in the Mendips and at Tortworth, Gloucestershire (Smith, 1985). This extent is not shown in the map at Figure 3, because the depths have not been calculated from the sonic velocity data. The andesite volcanics in the Mendips, where they are quarried, are of Wenlock age, (428-423 Ma) and have a sonic velocity of 4572 ms^{-1} (Green and Welch, 1965). The Bicester borehole logs show a varied sequence with both low sonic velocity (soft) and high sonic velocity (harder) units. The average velocity of this sequence is rather low (3594 ms^{-1}), but this property would be expected to increase deeper in the subsurface.

Upwood and Warboys boreholes contain basement rocks which are of probable Ordovician ages based on surrounding evidence. Upwood reached coarse agglomerate and tuffs at about 190 m below surface. Warboys borehole found porphyritic diorite which was extensively jointed with mineralisation at 170 m below surface. These boreholes are separated slightly from the Mountsorrel-type aeromagnetically-defined line of intrusions. The intrusions contain high levels of magnetite which produces positive magnetic anomalies. This line of intrusions extends from Hathern, Leicestershire through the Mountsorrel outcrop towards Peterborough.

Precambrian rocks lie unconformably beneath Lower Cambrian at outcrop (where they are quarried, e.g. Nuneaton, Charnwood) and beneath the Variscan unconformity at a couple of boreholes, near to the outcrop (Orton, Oxendon Hall) at depths from surface of 218 m and 232 m respectively. Tuffs were encountered at 336 m below the surface in Hollowell borehole and a prominent gravity low to the east of this borehole was modelled as granite rising to above 1000 m below surface (Allsop *et al.* 1987) but overlain by the Carboniferous Northampton Basin. Precambrian volcanic rocks have also been drilled at a depth of 1035 m below surface in the Withycombe Farm borehole (beneath Lower Cambrian). Logs indicate a high density (2.83 g/cm^3) and sonic velocity (5620 ms^{-1}), confirmed by laboratory tests giving saturated densities (2.78-2.85 g/cm^3) and porosities of 0.6-0.9% (Poole, 1978). Bletchley Station borehole is an old record (drilled in 1887) in which subsequent re-interpretation (Davies and Pringle, 1913) suggests that Lias sandstone with basement clasts was reached at terminal depth, probably lying just above the basement. The clasts, which were not kept, have been described as granite, Charnian and 'finely crystalline quartz-felsite with green mica'. A magnetic high, trending E-W lies just south of Bletchley Station borehole and may indicate igneous basement, which merges southwards into the NE extension of the Islip Anticline, where the Ordovician-Silurian volcanics are mapped.

Sandstone Rocks

The examination of sandstone extraction is complicated because many formations are worked for building stone rather than aggregates and many of the building stone quarries also sell small quantities of aggregates as a 'by-product'. Although a large number of sandstone formations have high Polished Stone Value (PSV), not all of them are suitable for use as aggregates because they are frequently friable, porous (meaning they will be damaged by frost) and weak. However, more indurated sandstones, such as greywacke (also often known as 'gritstone') are generally stronger and as a consequence are very valuable rocks for road surfacing applications. Although published PSV range from 60 to 70, it is frequently the formations with the highest values that have the poorest Aggregate Abrasion Value (AAV), i.e. around 12, which would make them unsuitable for road surfacing materials. Consequently, it is often sandstones with PSV of around 63 to 65 that typically have AAV of around 3 to 6, and these are most valuable.

The South Wales quarries in the Brithdir and Hughes members and Grovesend Formation of the Warwickshire Group have some of the highest PSVs combined with appropriate AAVs. Equivalent sandstones occur in a north-south line from outcrop in Warwickshire to Oxford and Berkshire and also in Kent, as shown in Figure 3. However, this does not necessarily mean that these rocks in England have similar PSV or AAV to those in South Wales. It may be that they have been less deeply buried during their geological history and consequently that they are less indurated (hard). In addition, these sandstones contain saline water in Kent, potable water near to the outcrop in Warwickshire and gas in Oxfordshire.

Jurassic Limestone Rocks

The youngest group of rocks which may have some potential for underground mining of aggregates is the Great Oolite Group (GOG, Middle Jurassic, 161-175 Ma). This group comprises two main, thick limestones (Great Oolite and Inferior Oolite) and interbedded middle shalier formations (Fuller's Earth). Typical Jurassic-aged limestones on the surface have AAVs that are greater than 16, and therefore they are only suitable for use in less demanding aggregates applications. PSVs for Jurassic-aged limestone are not generally recorded but are likely to be less than 40. However, based on the sonic well interval velocity comparison between the GOG and the Carboniferous Limestone a similar level of induration and porosity loss of GOG limestones is achieved at a depth of about 600 m. Uplift from a depth similar to Godley Bridge can then be interpreted for the Detention and Wallcrouch boreholes. The two values for Detention are because the sequence is repeated by faulting. Many of the Weald Basin boreholes show uplift from earlier deeper burial, making the harder limestones more accessible.

Probably the best place for investigation of Jurassic limestones is near the Mountfield-Brightling Purbeck Inlier and the nearest borehole is at Brightling, as shown on the map at Figure 3. Jurassic limestones at shallower depths on the London Platform to the north have not achieved the necessary burial to reach this value (e.g. Aston Tirrold). Limestone has been mined in the Mountfield Jurassic inlier in the past but no workings are currently active (this was probably the Purbeck Limestone for building stone). Gypsum was also mined at Brightling. Nearby the GOG top lies at 708 m below surface with the base at 856 m below surface. Gas is likely to be a hazard here within the Upper Jurassic (i.e. above the GOG).

Results of Economic Feasibility Study

Of the complete set of 62 boreholes that were considered in the research, the land designation screening process eliminated 20 from consideration and a further 11 were eliminated as the intersection thickness was less than the minimum for room-and-pillar mining, 8 metres.

In the case of each technically feasible prospect, the optimisation process, constrained only by the requirement that the mine production life be capped at 50 years, converged on a room-and-pillar mining method and a production rate of 3.5 MTPA. The latter production rate is the largest available in the mine production cost model and represents a relatively high output for an underground mine adopting the room-and-pillar method of mining. The lowest DCAD(10%) of the underground mines is £13.03/tonne which should be compared with £10.97/tonne for the Reference Leicestershire Superquarry. Results for the top six underground prospects are presented in Table 12. The trend identifiable in this subset of the results is that the DCAD(10%) increases with increasing depth of the potential aggregate horizon, and reduces with reduced distance from the target market area. Despite its greater distance from the target market area, Chitty outperforms Bicester because it processes the less demanding limestone material rather than volcanic material (meaning that the plant capital and operating costs are lower).

Production from the top four of these six prospects would amount to 14 million tonnes per year which approximately matches the 13.4 million tonnes per annum that was imported into the South East area of England in 2005 (Mankelow *et al.*, 2005).

Capital expenditure for the underground mines depends primarily upon the depth of workings and the aggregate geology and in all cases is higher for the underground mines than the reference surface case. Of all prospects evaluated the lowest capital expenditure amounted to £120.73 million for an adit access mine accessing workings at 115 metres depth through dry measures (Bletchley). This prospect did not feature in the top six ranked prospects because the assumed prospect resource scale could only support an 8 year production life at 3.5 MTPA, which had the effect of pushing the DCAD(10%) higher, and indicates a sensitivity of the results on prospect scale, an issue that, at this stage, will only be resolved with detailed site investigation. Lower production intensity underground mining operations for this prospect were considered as part of the mine design optimisation process, but led to higher DCAD(10%) values indicating that adoption of bulk methods of mining is as important as mining depth in establishing the competitiveness of underground aggregates mining operations. A Leicestershire Quarry delivering crushed rock aggregate at a rate of 1.25 MTPA returned a DCAD(10%) of £16.48/tonne indicating that underground operations operating closer to market, but with larger production intensities, could compete favourably with remote surface operations with production intensities lower than the reference case.

An opportunity to structure the outcomes by ranking the 31 prospects passing screening, by increasing DCAD(10%), has been taken to produce an underground aggregates mining 'merit order' (cheapest producers first) and plotting these values against the hypothetical cumulative annual aggregate produced by these ranked prospects (Figure 4). The ranked values of cost can be compared with increasing delivered price for aggregate to indicate which of the prospective mines would produce under the economic break-even condition implied by the DCAD(10%). The result is that the ranked

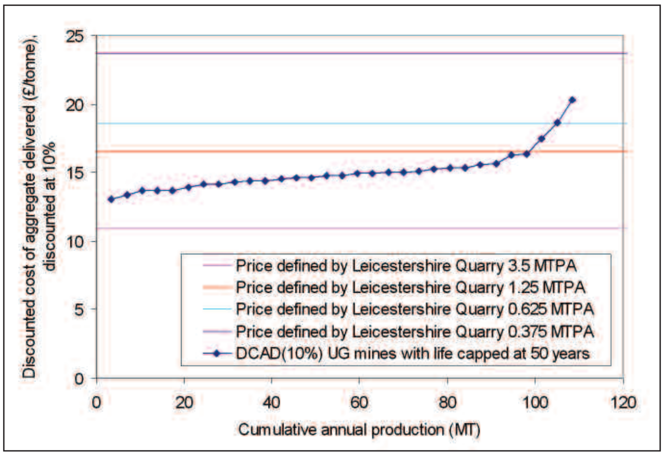

Figure 4. *Underground aggregates prospect supply curve for the South East area of England also showing DCAD(10%) values for the reference surface aggregates quarries of varying production intensities.*

Prospect	Distance to M25	Depth	Access	Aggregate Geology	CAPEX (£million)	DCAD(10%)
Chitty	45 miles	344m	Shaft	Carboniferous Limestone	135.22	£13.03/tonne
Bicester	35 miles	386m	Shaft	Volcanics	139.86	£13.38/tonne
Sonning Eye	19 miles	593m	Shaft	Basalt	147.33	£13.65/tonne
Stodmarsh	44 miles	654m	Shaft	Carboniferous Limestone	137.60	£13.66/tonne
Fleet	47 miles	582m	Shaft	Carboniferous Limestone	134.77	£13.71/tonne
Steeple Aston	43 miles	611m	Shaft	Basalt	143.91	£13.93/tonne
Reference quarry, 3.500 MTPA	70 miles	'-	'-	Igneous	92.07	£10.97/tonne

Table 12. *Prospects with the lowest DCAD(10%) for a 50-year mine life.*

values effectively form an estimate of the supply curve for the potential UK underground crushed rock aggregate industry.

Underground aggregates prospects within the supply curve of Figure 4 plotting below a given price level should be interpreted as effectively competing within the South East area of England aggregates market; those plotting above a given price level should be interpreted as not being able to effectively compete at that price. As these local producers would face a competitive market (in the positive economic sense), with a minority market share in comparison with established large scale surface quarry crushed rock aggregate producers, the surface quarries would define this market price (the price makers) and, at least initially, the underground mines would have to be able to operate economically facing this competition (the price takers).

ROYALTIES

It is an increasingly frequent circumstance that instead of procuring freehold and hence rights to exploit aggregates within the freehold, aggregates operators procure mineral rights from a 3rd party freeholder and do not take outright title of land, but take a lease. In securing the mineral rights rather than freehold, a royalty becomes payable to the freeholder. From the 2008 UK Minerals Yearbook (Bide *et al.*, 2008), the UK average royalty paid to freeholders for aggregates was £0.45/tonne, rising to £0.65/tonne and £0.90/tonne for the East of England and South East regions of England respectively. In the prospect valuation model, the following revisions were applied:

- the effective operating cost per tonne was increased by the royalty amounts; and,
- the total capital expenditure was reduces due to no longer requiring the procurement of freehold title.

All other things being equal, the effect of not securing all the freehold of the land within which the aggregates will be exploited caused a rise in the DCAD(10%) across competitive prospects of 6 to 7%; the increase in input costs was not compensated by the reduction in total capital expenditure.

CONCURRENT USE REVENUES AND AFTER-USE CAPTIAL CREDITS

Undoubtedly concurrent use of land above underground aggregates mines not used to accommodate the surface infrastructure, and after-use developments of both surface land holdings and underground void created by aggregates mining, will add a multiplicity of additional development complexity arising from environmental, planning, public perception, public health, even human rights considerations. The scope of the research did not allow for investigation of these complex issues but confined itself to establishing whether or not there may be economic justification for detailed consideration of underground aggregates mines integrated with conventional industrial, commercial, retail and residential developments.

Within the valuation models, land holdings were divided into:

1) that portion of land required for construction of the surface facilities of the underground aggregates mine, including the crushing and screening plant (the surface footprint of the underground aggregates mine), and;
2) that portion of land that lies outside this surface footprint but will also be undermined by the extraction operations.

At the end of production, land holdings of Type 1 could be sold with a particular land-use in mind, after it has been remediated. Land holdings of Type 2 would not require remediation at the end of production and could be sold for development, but these holdings could also support an economic use beneficial to the aggregates operator that is concurrent with aggregate production activities. Sub-surface void may also have appreciable value given the land pressure and urbanisation of the South East area of England.

Long aggregates mine lives, for example 50 years, would realise Type 2 land available for concurrent uses that could produce auxiliary revenue streams of value to the aggregates operator. The contribution to prospect net present values, of capital credits arising from sale of land or void many years into the future, was found to be significantly diminished by the discounting process. Consequently after-use capital credits were found not to be relevant in this scenario.

Short aggregates mine lives, for example 15 years, did not generate a requirement for Type 2 land to be procured in all but the very deepest prospects where extraction ratios were very low. Only in these exceptional cases would mine workings be expected to extend beyond the boundary of the mine surface footprint. Consequently auxiliary revenue streams from concurrent uses were found not relevant in this scenario. Capital credits arising from the sale of surface land or underground void were found to remain significant in this scenario because the diminishing effect of discounting is appreciably reduced with short production lives.

The effect of capping the production life of prospects at 15 years, while ignoring any after-use capital credits was to increase the DCAD(10%) of the more competitive underground aggregates mines by ~7% in comparison to the 50 year production life cap scenario without concurrent use revenue benefits.

In comparison to this situation, 15 year producing life prospects that considered after-use capital credits had lower DCAD(10%). The magnitudes of these reductions were found to be dependent on the specific type of after-uses, as exemplified in Table 13 for the Chitty prospect.

A pessimistic but pragmatic combination of after-uses is probably remediated land sold for industrial use with underground space sold at industrial land use rates too, which leads to a reduction in the DCAD(10%) of ~7%. The rationale for selling land and void at higher value than procured is that after aggregates production has ceased and having been remediated, this same land at least benefits from being serviced with power, drainage, telecommunications, etc. as a result of the mine

Remediated surface land after-use	Underground void after-use		
	Agricultural development, e.g. biomass plant	Industrial development	Commercial development, e.g. office space
Agricultural, development, e.g. wind farm.	0.07%	2.06%	2.35%
Industrial development	5.20%	7.19%	7.47%
Small residential development	13.67%	15.66%	15.87%
Bulk residential development	12.19%	15.23%	15.44%
Retail development	27.90%	29.75%	29.96%

Table 13. *Improvement of DCAD(10%) for the Chitty prospect arising from after-use capital credits for remediated surface land and underground void under the scenario of a 15 year aggregate production life. The 15 year base case DCAD(10%) for the Chitty prospect was £14.05/tonne.*

development activity that formerly took place upon it. The same can be considered for the underground space created. The space will benefit from power, drainage, telecommunications and ventilation services as a result of the mine development, and as such, industrial, serviced, land value rates are taken to be appropriate in determination of possible sale values credited in the valuation models.

This pragmatic combination of after-use scenarios for a 15 year producing life leads to reductions in the DCAD(10%) that are of the same order as the increases in DCAD(10%) that arose in considering the reduced production life relative to the 50 year production life scenario. A more optimistic practical combination is probably remediated land sold for a retail development on surface with underground space sold at industrial land use rates which leads to a reduction in DCAD(10%) of ~30%. This indicates that shorter producing life mine designs could readily out-compete the more remote reference surface quarries if higher after-use values can be entertained. In these cases, the mine stope layouts could be designed primarily for the intended after-use, rather than the aggregates production process. These observations, exemplified for the Chitty prospect do not change significantly for the remaining prospect locations. Modifying the assumed discount rate does not change these general observations significantly either.

For longer operating lives (i.e. those evolving from the 50-year operating life cases) when a concurrent surface use is entertained by the aggregates operator as the owner of land outside the underground mine surface footprint (Type 2), the aggregates operator may aspire to benefit from all the resulting rental for the land after it is developed and is being used. There is unlikely to be as much freedom over development of concurrent use of land because the issue would have to be debated in the process of any original grant of permission, and restrictions are likely to be the price of securing permission. In order to realise any potential economic benefit concurrent with aggregates extraction, there is a probable need for ownership for concurrent developments by the aggregates operator in order that any restrictions or obligations are allocated and properly discharged. Consequently, one outcome that may have to be entertained by the aggregates operator is that they may have to additionally adopt the role of Client for the concurrent development, in turn requiring additional commitment of capital, over and above that required to bring the aggregates mine to an operational state. Not all aggregates operators will be comfortable with this concept, but nevertheless computations reflecting the outcomes of such a policy are presented here, for completeness.

The DCAD(10%) with a 50 year aggregate producing life was recalculated considering various potential concurrent uses in turn. Results of these computations are exemplified for the Chitty prospect in Table 14. Discounted cash flow models were established for the concurrent use project and this and the discounted cash flow model for the mine were simultaneously optimised through a search for the break-even price of crushed rock aggregate when the discount rate was set at 10%. The scale of each concurrent development project, expressed in terms of the land area it would occupy, was allowed to vary, but was capped at the typical land take for such projects, present in the case studies that were reviewed as part of the research (see Brown et al., 2010). As a cash flow analysis was undertaken for the concurrent project, the values for the time to complete the development and the development project life were estimated, based on the case studies reviewed.

Table 14 shows that there are particular cases where a concurrent surface development leads to reduction in the DCAD(10%), e.g. agricultural, small residential, and so-called Private Finance Initiative (PFI) projects such as sewage treatment works or barracks (relative to the case where no concurrent use is considered). Ultimately all the results in Table 14 depend on either i) Valuation Office Agency data for lease and rental yields or ii) the unitary charge values for PFI projects of varying types, relative to the 10% discount rate used to determine the DCAD. Concurrent projects with expected return rates less than the 10% discount rate end up being subsidised by the value in delivered aggregate from the mining operation (NPV(10%) Mine > 0, NPV(10%) Concurrent Use < 0). Concurrent uses that lower the DCAD(10%) are those with expected return rates greater than the 10% discount rate used (NPV(10%) Mine < 0, NPV(10%) Concurrent Use > 0).

Concurrent Use	Development Time (years)	Development area (ha)	Project Life (years)	DCAD(10%) (£/tonne)	NPV(10%) Mine (£M)	NPV(10%) Concurrent Use (£M)
Agricultural	0	X	20	13.02	-0.07	0.07
Residential-small	2	1	20	13.03	-0.01	0.01
Residential-bulk	2	10	20	15.20	44.23	-44.23
Industrial	2	10	20	13.50	9.73	-9.73
Commercial	2	5	20	15.62	52.89	-52.89
Retail	2	5	20	14.28	25.54	-25.54
PFI-Sewage Treatment Works	2	9	25	11.75	-25.89	25.89
PFI-Barracks	2	5	50	12.79	-4.73	4.73
Wind Farm	1	X	25	13.08	1.10	-1.10

Table 14. *Economic performance of the Chitty underground aggregates prospect with various concurrent developments on Type 2 land. The 50 year base case DCAD(10%) for the Chitty prospect was £13.03/tonne. X = Up to available area.*

It should be noted that in none of the cases listed was the DCAD(10%) reduced to the point of out-competing the Leicestershire Superquarry reference case of £10.97/tonne. However, in situations where the source of capital for the concurrent development is different from that for the underground aggregates mine (perhaps best visualised as joint venture arrangements between an aggregates operator and a conventional land development company) substantial reductions in DCAD(10%) may result because the aggregates operator would enjoy concurrent rental revenues for the Type 2 land without having to commit capital to realise the concurrent development. For this case, the coupled optimisation of concurrent projects used to compile Table 14 is inappropriate.

Conclusions

1) The review of the deep geology in the south east area of England has identified areas with formations that could potentially be suitable for crushed rock aggregates. These are presented on Figure 3.

2) Locations of 62 deep boreholes, where records held by the BGS indicated the presence of potential aggregates horizons, were adopted as representative prospect sites for underground aggregates mines. A screening process reduced this list to 31 'prospect' sites by removing those within urban areas or sensitive land designations, or those with intersection thicknesses which were two narrow to support bulk mining methods.

3) Synthesis of cost models for environmental compliance, decommissioning and after-care revealed that the magnitude of the respective costs for surface quarrying and underground aggregates operations are rather similar, especially when compared against the magnitude of project development capital expenditure for either type of working method.

4) The industrial partner in this research, as well as other industry consultees, understandably proved nervous about releasing historical cost information or providing access to their own standard costing systems for research purposes. However, the same parties welcomed the opportunity to provide feedback on production and transportation cost models formulated by the research team, and this feedback was used to help ensure that the cost models used in subsequent parts of the research were reasonably accurate and applicable to the UK aggregates industry. Consequently, this method of establishing meaningful production and transportation cost models for research purposes was found to be effective. The production cost models presented as part of this study should thus prove useful to other researchers.

5) Exhaustive enumeration search techniques for each of the 31 prospect sites identified room-and-pillar mining with a production intensity of 3.5 MTPA (14,000 tonnes/day) and mostly shaft access as mine design parameters that led to the most competitive discounted cost of aggregate delivered (DCAD).

6) The lowest DCAD(10%) determined across all 31 prospect locations was £13.03/tonne, 19% higher than the reference cost of £10.97/tonne from a Leicestershire reference quarry producing 3.5 MTPA serving the same market. Capital expenditures for the most competitive underground aggregates mines ranged from 1.46 to 1.60 times the £92.63 million estimated for the Leicestershire reference case. The surprise here is not that the values for the reference quarries are lower, rather that the values are so close. Underground mines with production intensity of 3.5 MTPA would compete favourably with Leicestershire quarries with production intensities of 1.25 MTPA.

7) All other things being equal, the effect of not securing all the freehold of the land within which the aggregates will be exploited caused a rise in the DCAD(10%) across competitive prospects of 6 to 7%; the increase in input costs due to royalty was not compensated by the reduction in total capital expenditure due to reduced land procurement cost.

8) Reducing the cap on aggregates production life from 50 years to 15 years increased the DCAD(10%) by ~7% for the prospect sites.

9) Consideration of after-use capital credits was found only to be relevant to aggregates mines with short production lives, here represented with a cap of 15 years. In the case of the exemplar prospect adopted, industrial development after-use capital credits for remediated surface land and the sub-surface void led to reductions in the DCAD(10%) of 7.19%, bringing such a scenario to par with a 50 year producing life operation. For 15 year producing lives, higher value after uses, for the remediated surface land, for example a retail development, led to reductions in DCAD(10%) of ~30%.

10) Consideration of auxiliary revenues arising from rental or lease of surface land for which freehold is procured but is not required to accommodate the surface footprint of an underground aggregates mine was found only to be relevant to mines with long production lives. In order to realise such potential economic benefits, the research considered that there was a probable need for ownership for concurrent developments by the aggregates operator in order that any restrictions or obligations are allocated and properly discharged. Consequently, one outcome that may have to be entertained by the aggregates operator is that they may have to additionally adopt the role of Client for the concurrent development, in turn requiring additional commitment of capital, over and above that required to bring the aggregates mine to an operational state. Aggregates operators are unlikely to be comfortable with this concept, especially because the economic benefits were found not to be appreciable and planning and consenting issues would become more complex. Joint venture arrangements between an aggregates operator and a conventional land development company could lead to substantial reductions in DCAD(10%) because the aggregates operator would enjoy concurrent rental revenues without having to commit capital to realise the concurrent development.

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